Computational Fatigue Models to Assist in Risk-Based Certification of Additively Manufactured Metallic Parts

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Today's Presentation

1. Introduction
2. Modeling and simulation approach
   - Machined specimens
   - As-printed-surface (APS) specimens
     - Surface roughness stress gradients
     - Surface material contour layer
3. Assess risk of adopting AM repairs and replacements
   - Probability of Failure
   - Fatigue strength
4. Integration of M&S into the certification process
5. Conclusions

Acknowledgements

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  - SBIR partner: Aerojet Rocketdyne, Dan Matejczyk
  - SBIR partner: UES/RoboMet®, Veeraraghavan Sundar
- USAF LCMC
  - TPOCs: Kirk Easterday, Howard Sizek
  - Technical Analyst: Emmanuel De Leon

VEXTEC Introduction




Headquarters

Nashville, TN – 20+ years in business

VPS-MICRO® Software

Predicting fatigue durability and risk of metallic products and systems

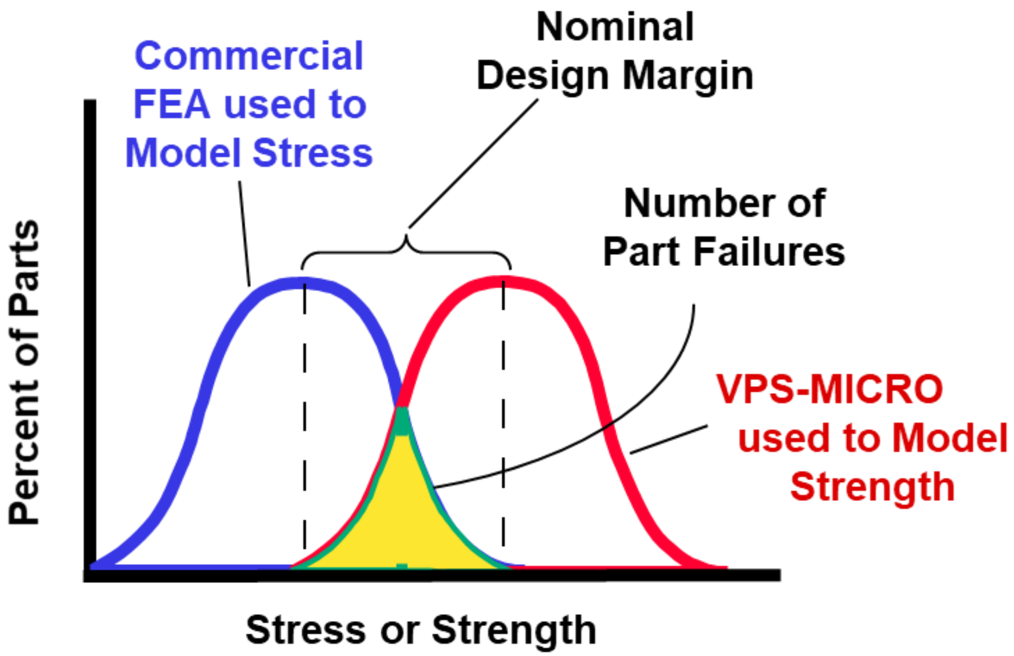
Value Proposition

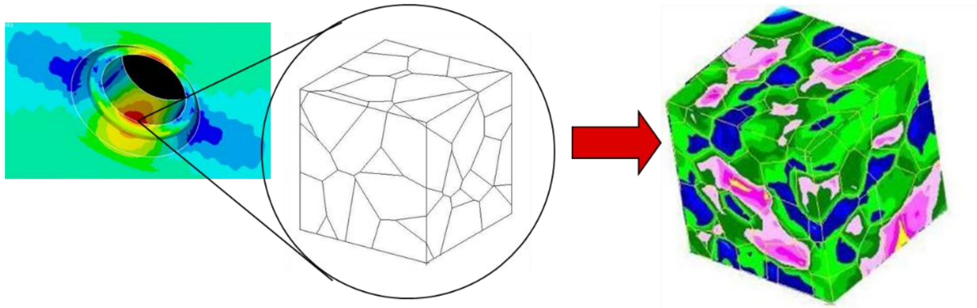
Supplement physical testing for increased confidence in accelerated qualification of parts

VPS-MICRO is:
Validated by US Government research programs
Utilized globally by commercial industries
Backed by 7 US Patents

Probabilistic Microstructural Fatigue Modeling

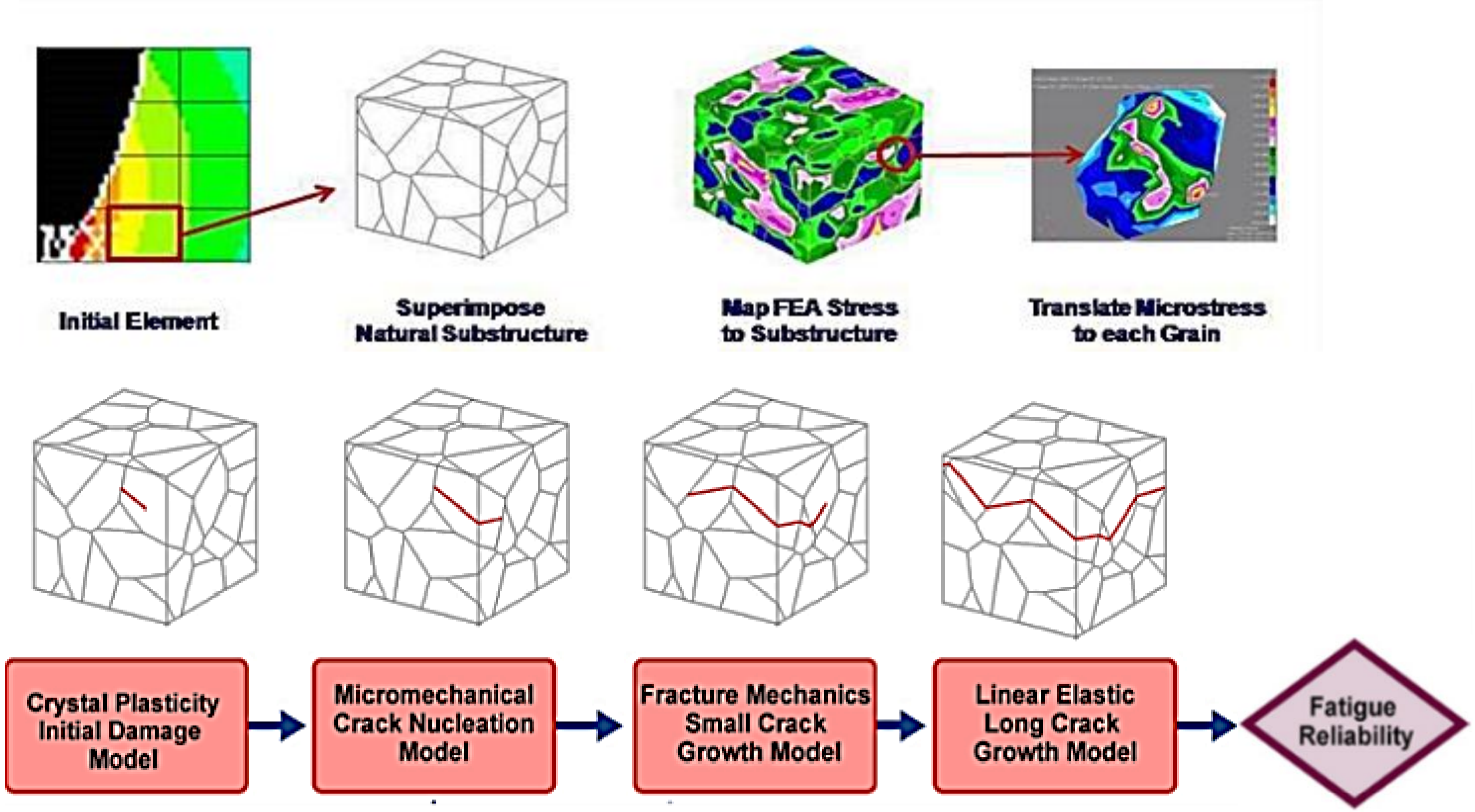
- Just as FEA uses a digital representation of the part to model the stresses, VPS-MICRO uses a digital representation of the material to model strength
  - –Fatigue strength is the big cost driver and is governed by the material microstructure
  - –Addresses fatigue strength
  - –Creates digital models of the material microstructure, utilizing physics of failure principles
  - –Simulates surface effects (roughness, carburization, etc.)



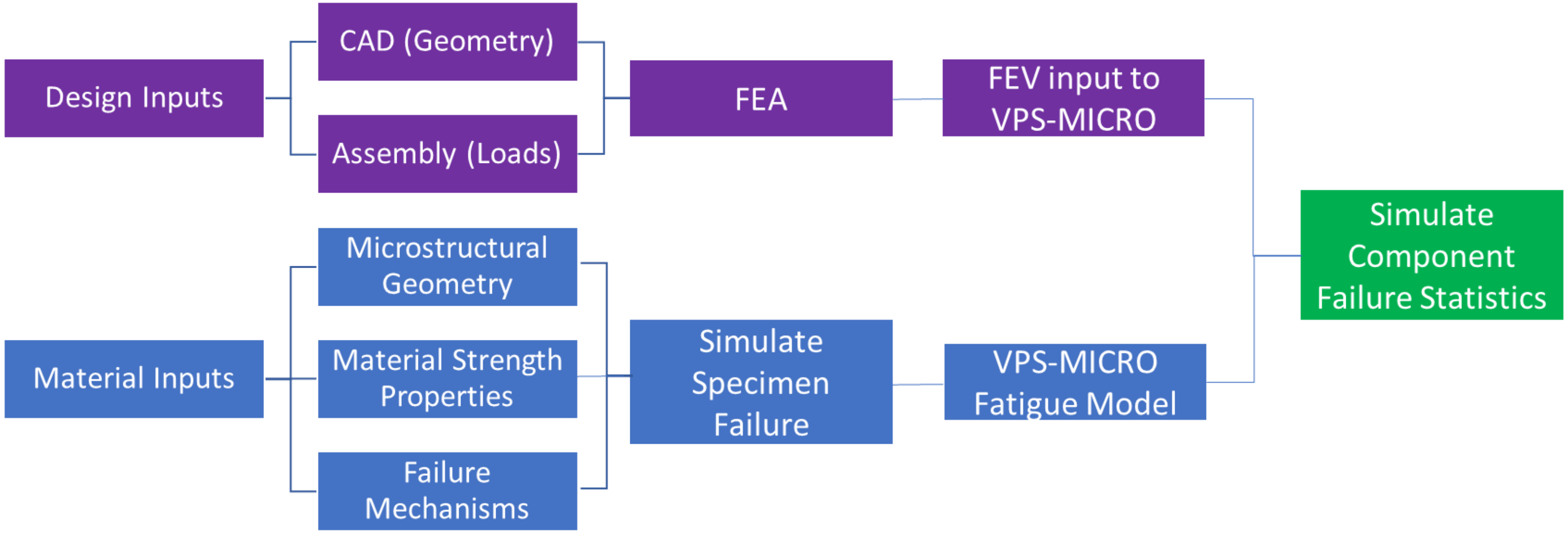


Standard Work Protocol (SWP) Builds the Virtual Twin of a Component

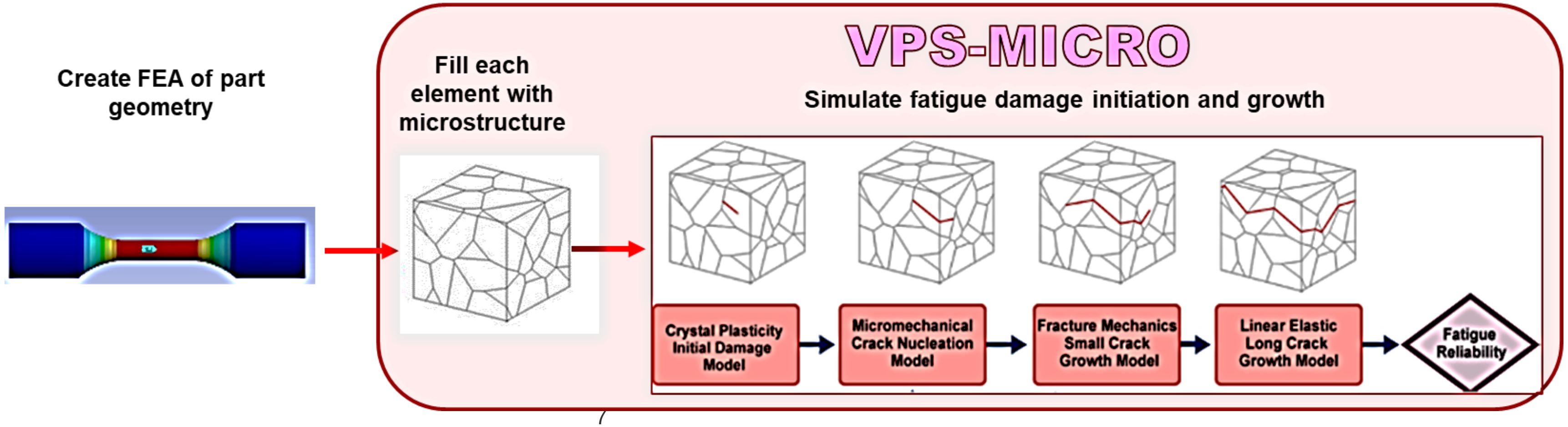
- SWP software links macrostructure FEA to microstructure
- The software can also take additional stress inputs for residual stress and K_t effects



Apply SWP to Smooth Round Bar Geometry



Smooth Surface Analysis



SWP Material Model Inputs

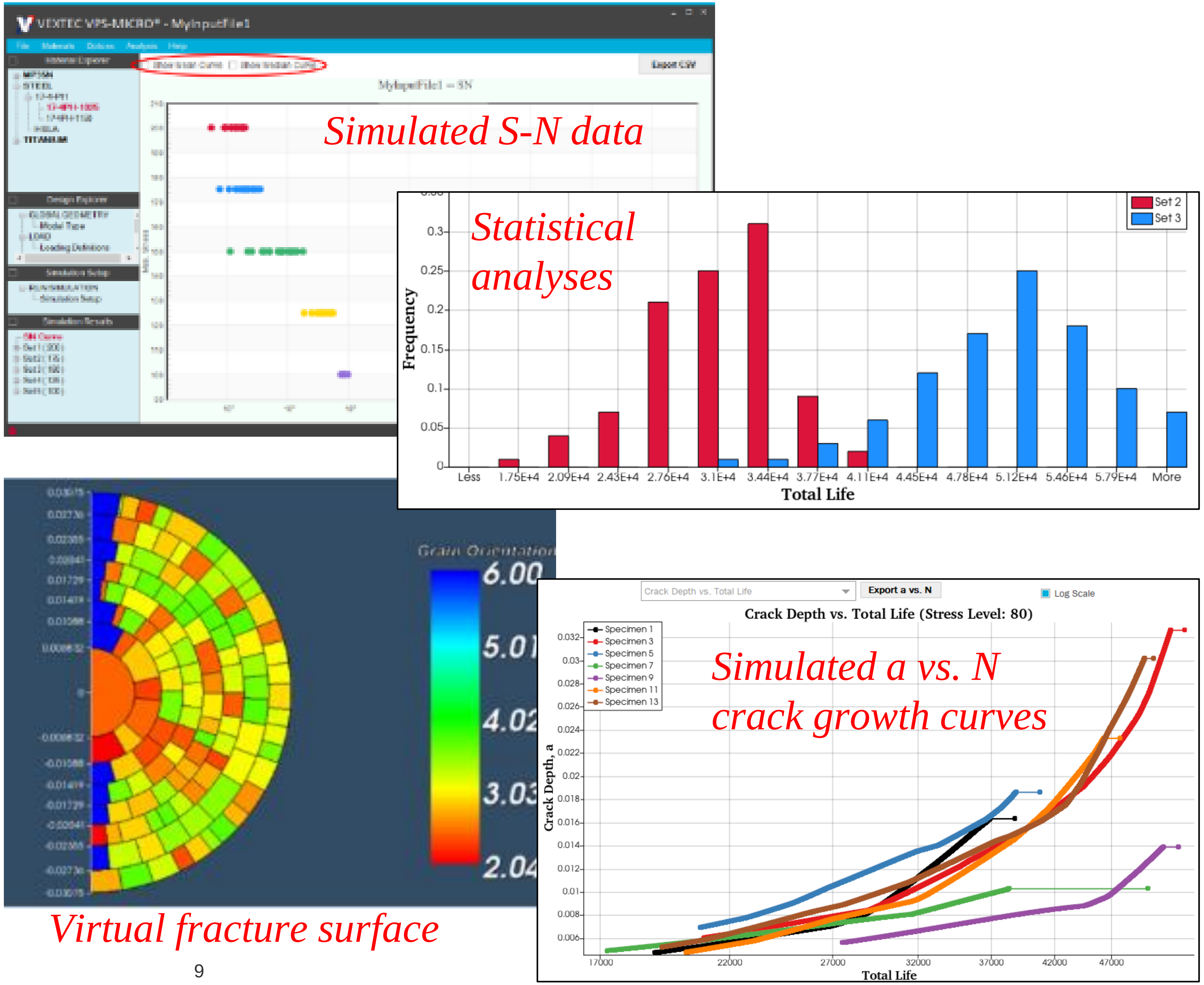
Material Model Parameter	Type	Typical Data Source
Shear Modulus	Deterministic value	Material data sheet for alloy/heat treat
Poisson's Ratio	Deterministic value	Material data sheet for alloy/heat treat
Grain Boundary Strength	Deterministic value	Threshold crack growth per ASTM E647 (slow rate; high R-ratio)
Short Crack Coefficient	Deterministic value	Used in this process as a calibration parameter
COV on Micro Stress	Deterministic value	Material system anisotropy (literature)
Specific Fracture Energy	Deterministic value	Proportional to the area under the stress/strain curve per ASTM E8
Grain Orientation	Probabilistic distribution	Material crystal system (literature)
Grain Size	Probabilistic distribution	Metallography (preparation per ASTM E3); measure per ASTM E1382
Frictional Strength	Probabilistic distribution	Cyclic yield strength per ASTM E606
Long Crack Growth (Paris Equation $da/dN = C\Delta K^n$)	n (deterministic value) C (probabilistic distribution)	Fatigue crack growth per ASTM E647
Defects / Voids / Inclusions	Size (probabilistic distribution) Population density (probabilistic distribution)	Metallography (preparation per ASTM E3); measure per ASTM E45 / ASTM E1245

Irrespective of the alloy, VEXTEC has a standard set of inputs for its fatigue modeling capabilities

Most of the input data can be obtained from standard material testing (ASTM)

VPS-MICRO Software Output

- Windows desktop tool (no HPC/cloud)
- Wide range of applications
  - Standalone tool for simple specimen geometry models
  - Integrate FEA models for complex geometry of full-scale components
- Outputs
  - Simulated S-N fatigue curve
  - Virtual fracture surface + crack growth
  - Detailed statistical analyses
- Customizable software product
  - Interface with standard FEA software
  - Predict risk of fatigue failure from complex in-service loading spectrums

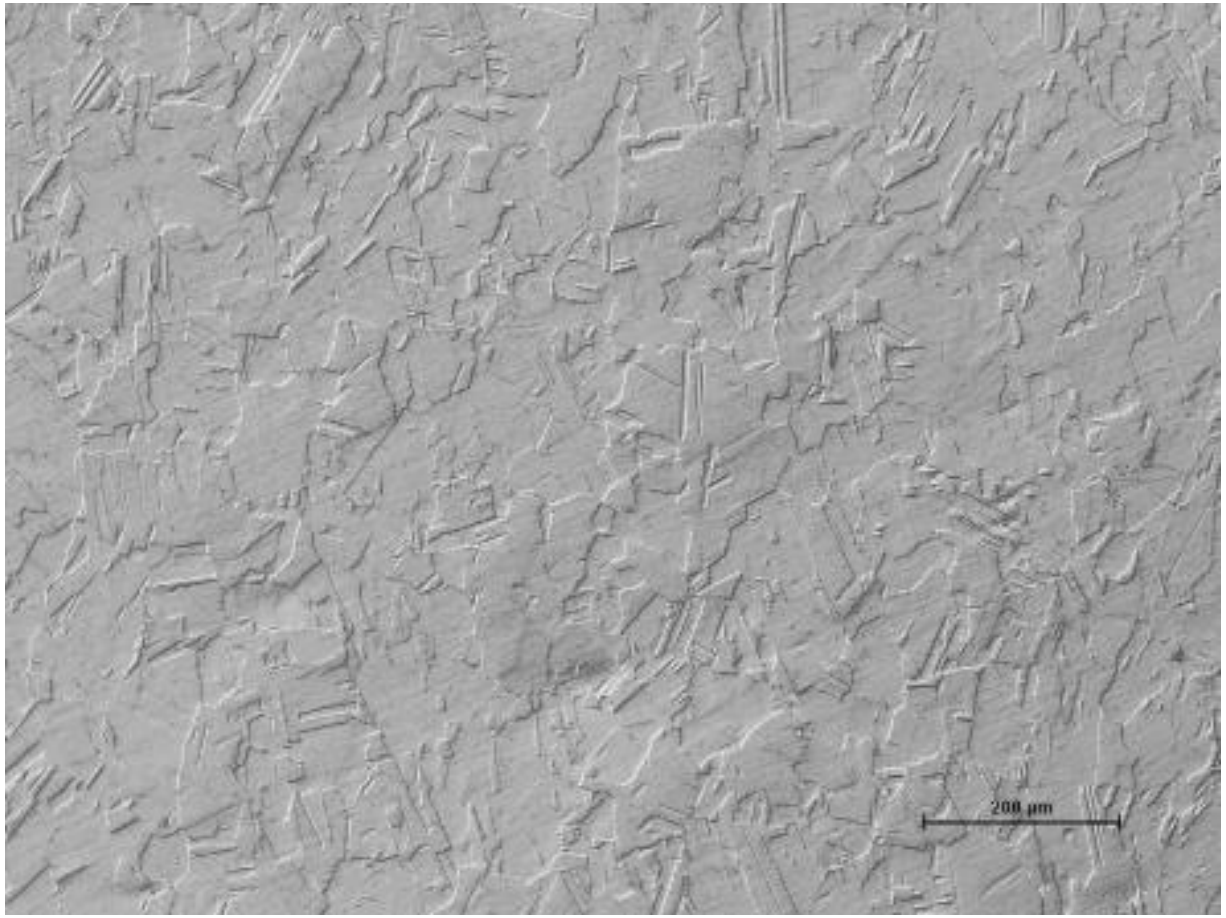


Software Partners:

ANSYS   SIMULIA

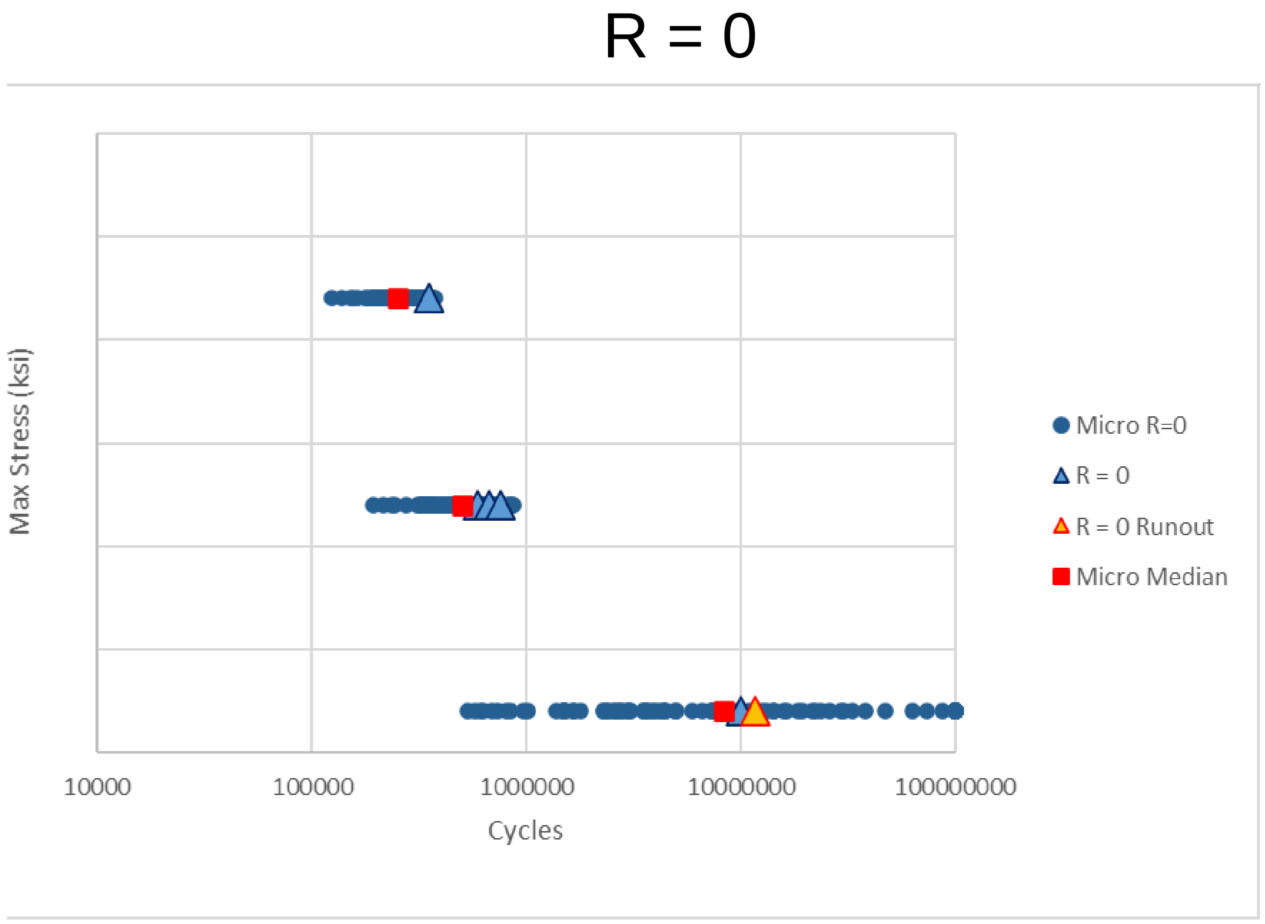
Example of IN625 Smooth Round Bars

- Model inputs for machined surface
  - Monotonic stress – strain to failure curves
  - Cyclic stress – strain curves
  - Fatigue crack growth curves
  - Cross section micrographs



Model Predictions for Machined Specimens

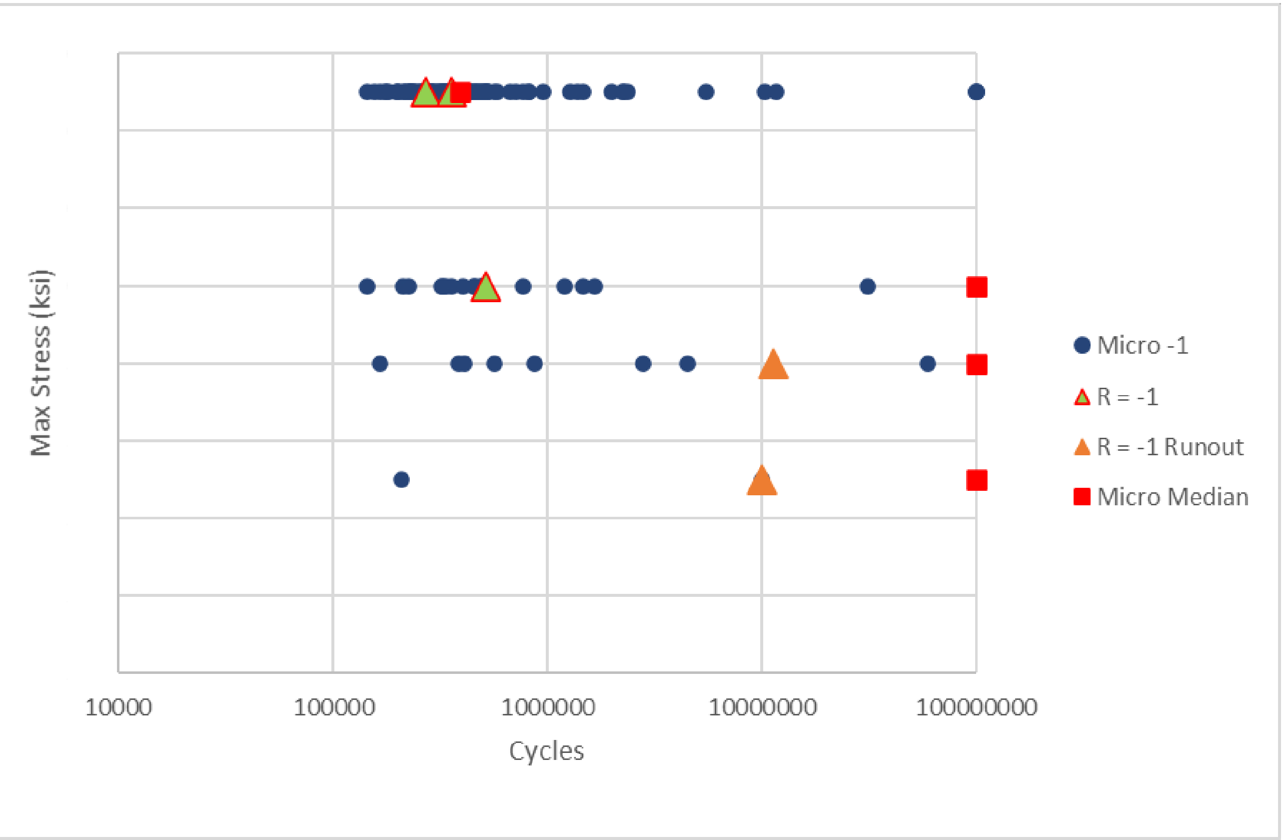
- 100 specimens generated at each stress level
- Each specimen has a different life because microstructure is different (but statistically similar) for each specimen
- Model is calibrated so average life is similar to test data at middle stress level
- Model predicts fatigue lives at high and low stress level



Model Predictions for Different Load Ratio

- Model calibrated to R = 0 material parameters used for R = -1
- Only max and min stress levels changed
- 100 specimens generated at each stress level
- Model predicts fatigue lives at different load ratio

R = -1



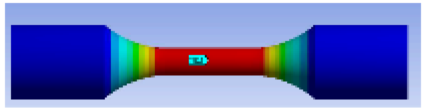
Computationally Predict Fatigue Debit of As-Printed Surface (APS) Geometry

- Computationally predict the fatigue knockdown due to the effect of metal additively manufactured APS geometry using digital engineering
  - Calibrate model to smooth specimens
  - Without modification to the smooth model material parameters, predict the knockdown in APS specimens
  - Important APS features included in the model
    - Stress gradients due to the crevices and pits in the specimen surface
    - Stress gradients due to build orientation surface undulations
    - Distinguish the material outer layer from the inner core (gradient microstructure)

Apply SWP to APS Geometry

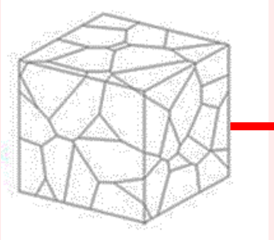
Smooth Surface Analysis

Create FEA of part geometry

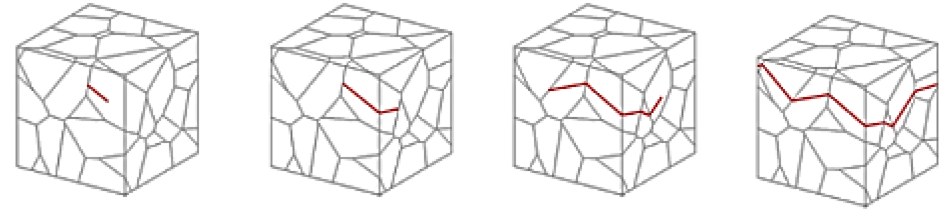


VPS-MICRO

Fill each element with microstructure



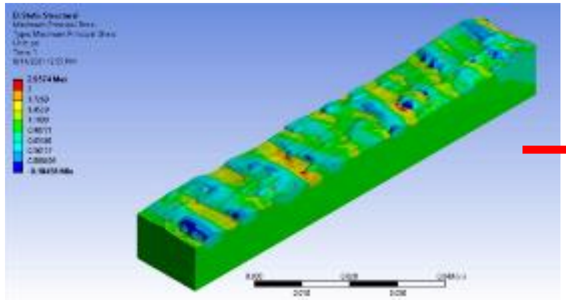
Simulate fatigue damage initiation and growth



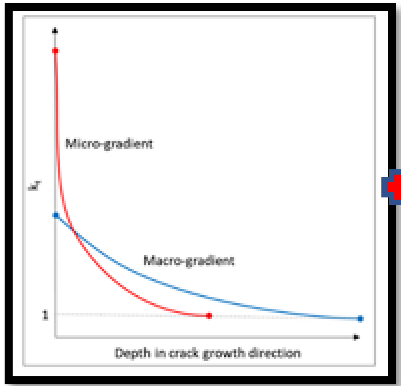
Crystal Plasticity Initial Damage Model → Micromechanical Crack Nucleation Model → Fracture Mechanics Small Crack Growth Model → Linear Elastic Long Crack Growth Model → Fatigue Reliability

As-Printed Surface Analysis

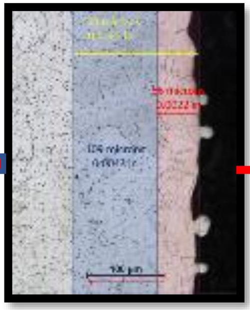
Create FEA of rough surface geometry



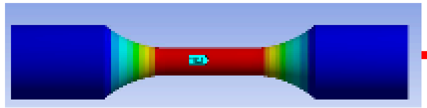
Predict surface stress gradients



Add APS layer properties

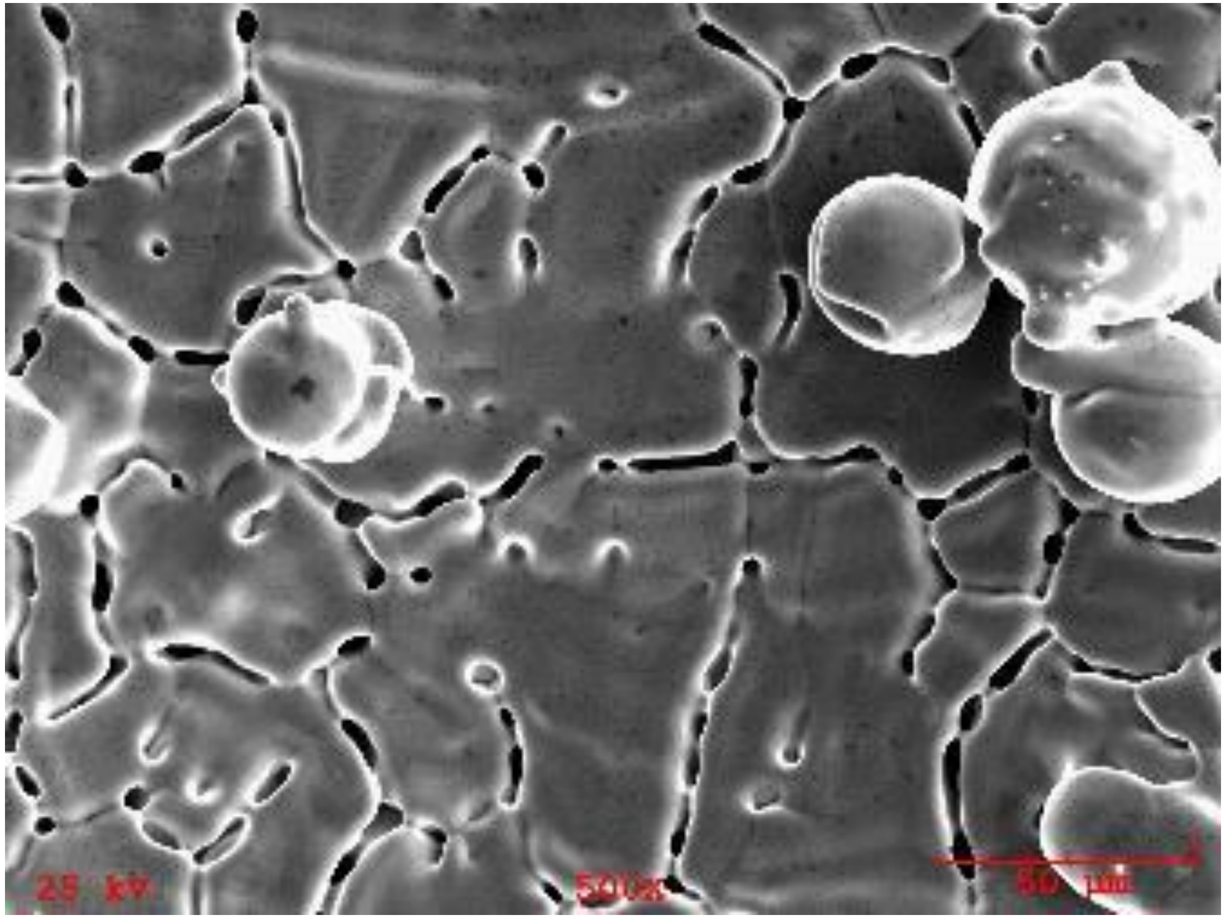


Superimpose surface stresses on smooth surface part FEA

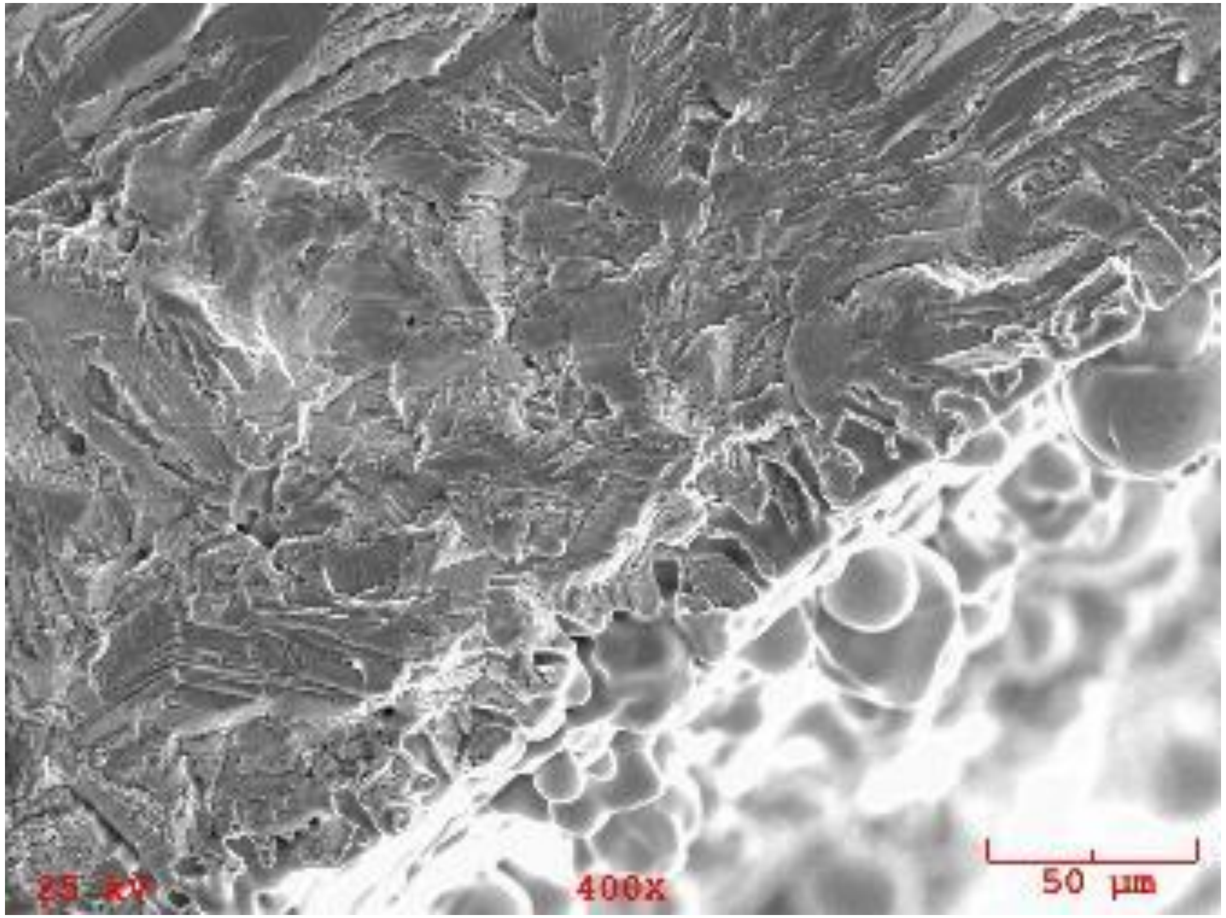


→ VPS-MICRO

As-Printed Surface



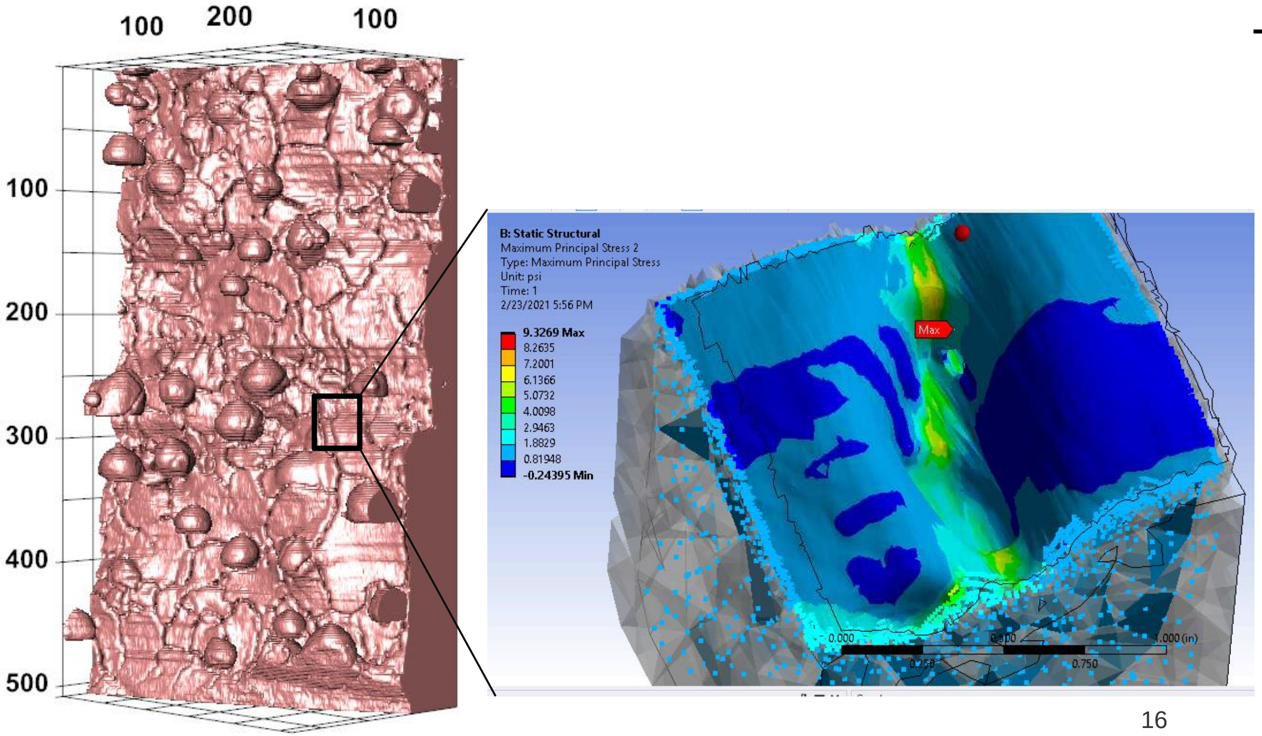
Geometry surface



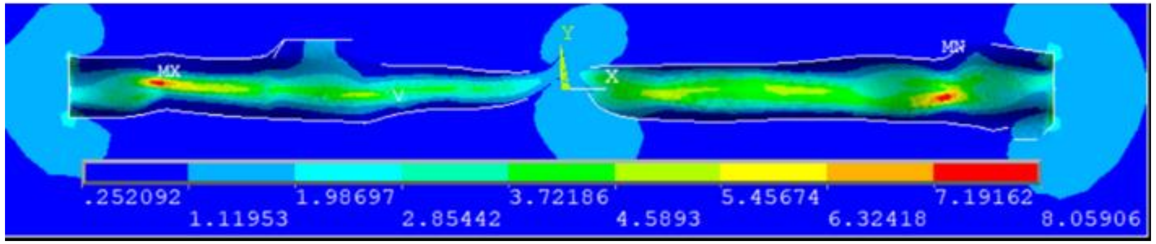
Cracks initiate in crevices

RoboMet Analysis – Vertically Built APS Specimen

- RoboMet serial sectioning
  - 1.5 µm/section removal rate
  - 500x total magnification
  - 0.1 μm^3 voxel resolution



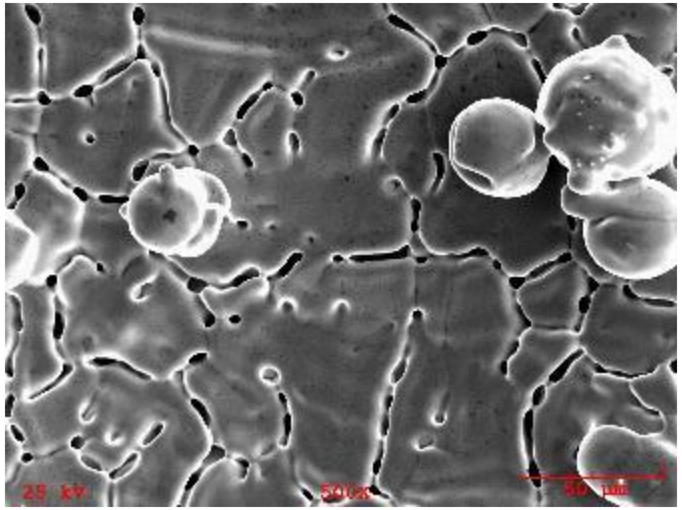
- STL file used to create Analysis FEM
  - Looked at several interacting geometries
  - Crevice interaction has minor effect on stress
  - Local geometry in crevice has the strongest impact



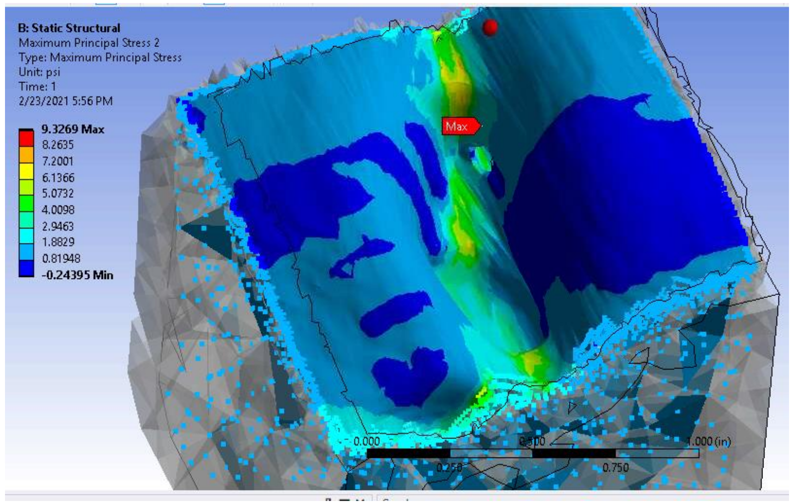
Surface Roughness Stress

- Spatial Distribution of K_t

Actual surface

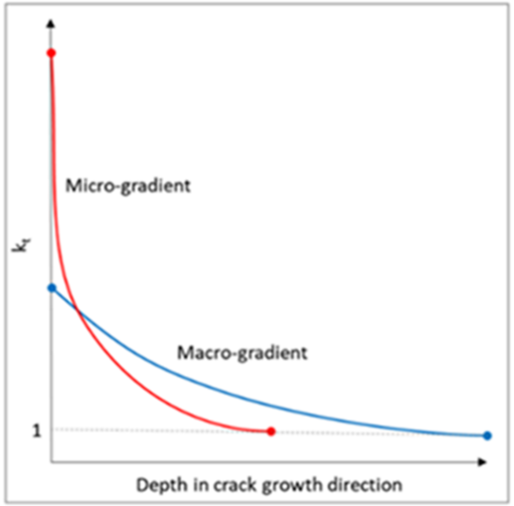


FEA of APS

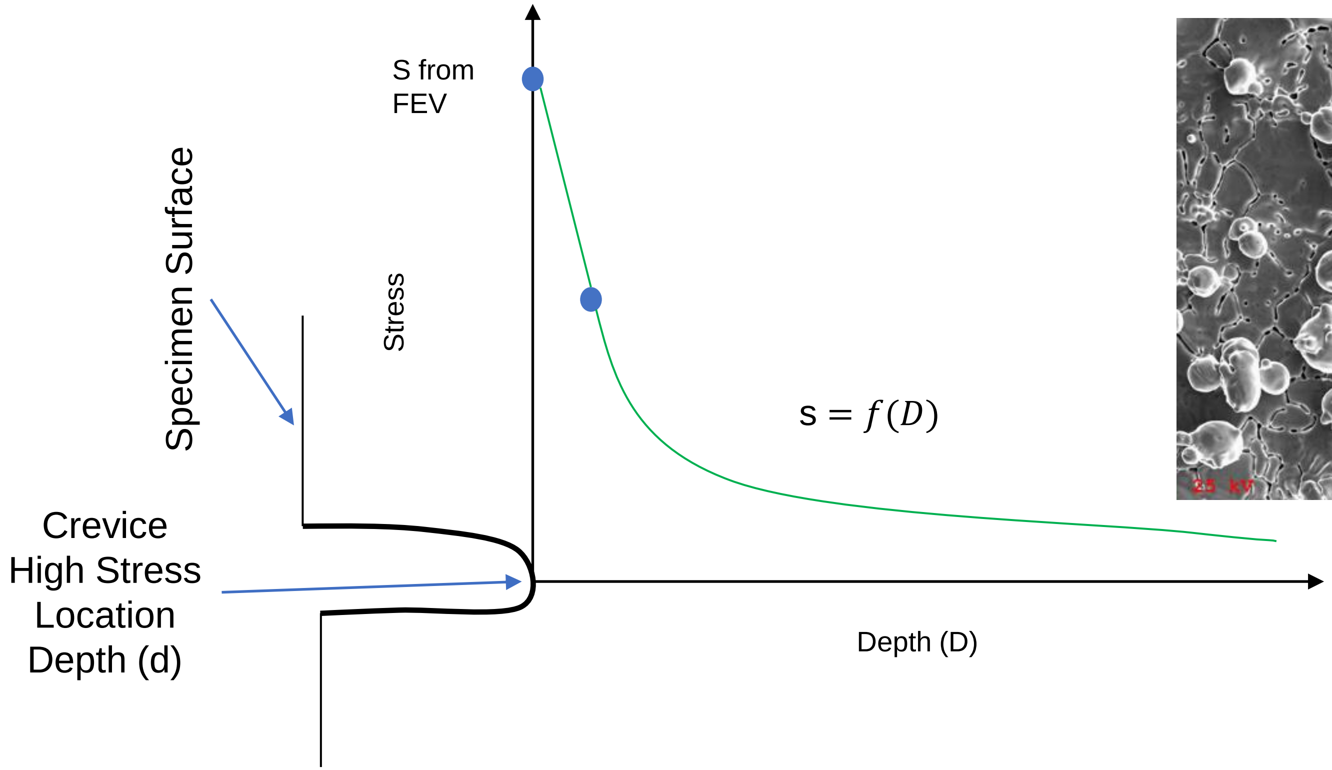


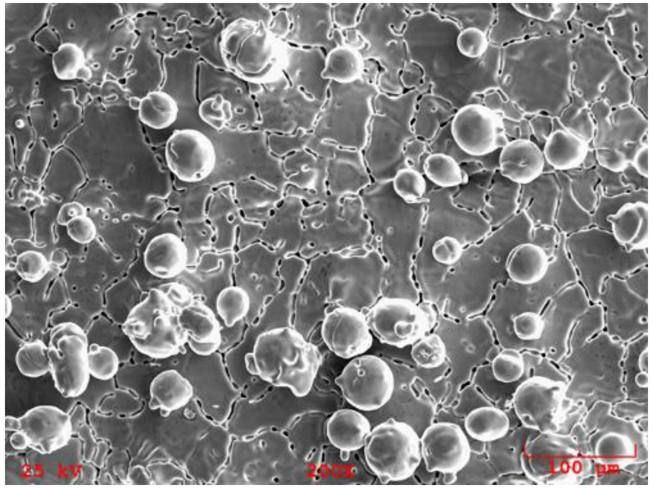
K_t field with random amplitude and frequency

Statistical K_t gradient



Modeling Random Field of Surface Stress Concentrations

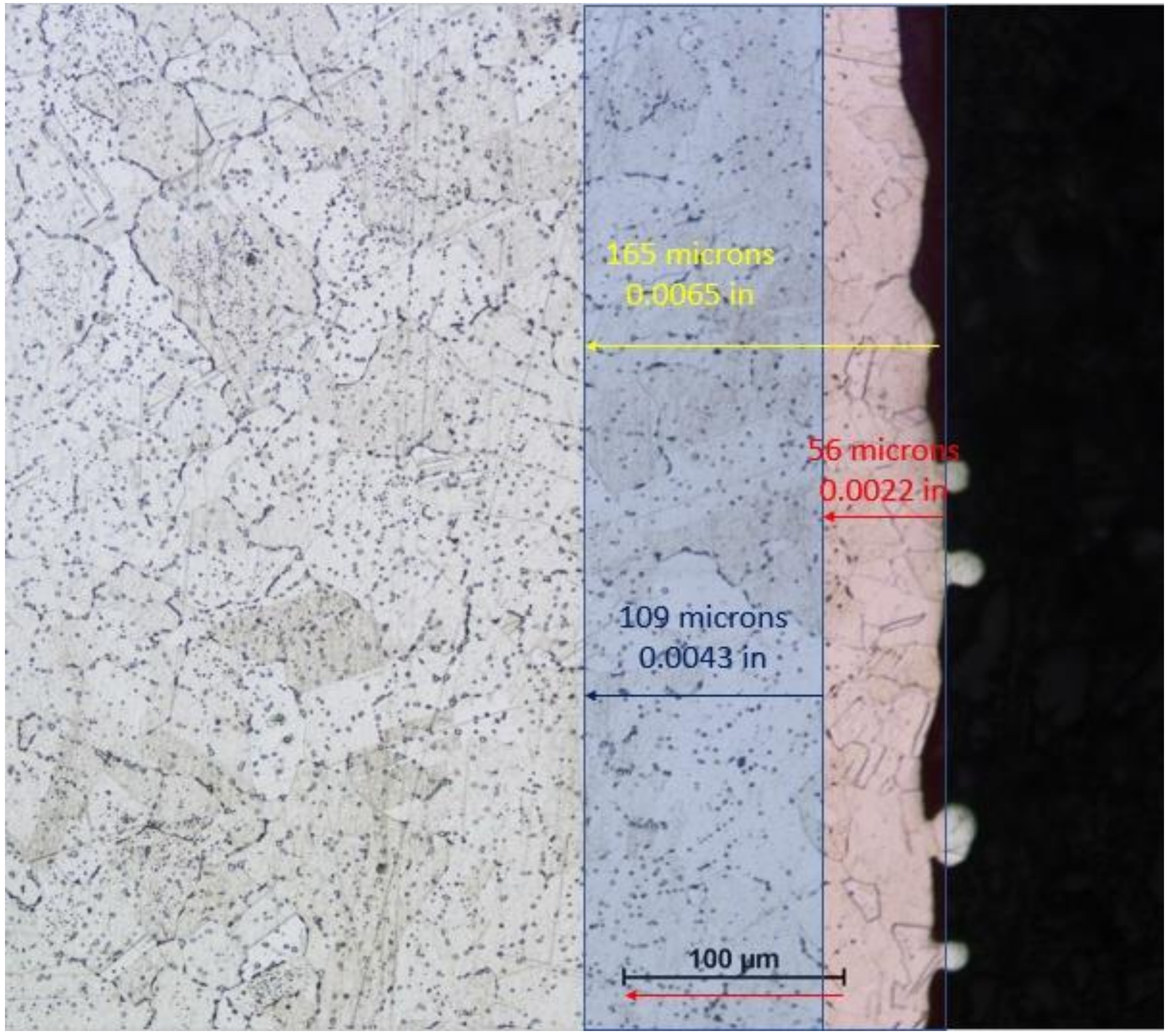




- Model generates a crack-like defect of size *d* and grows the crack into the depth *D*
- *d* and *s* are random
- Generates population of many defects per square inch

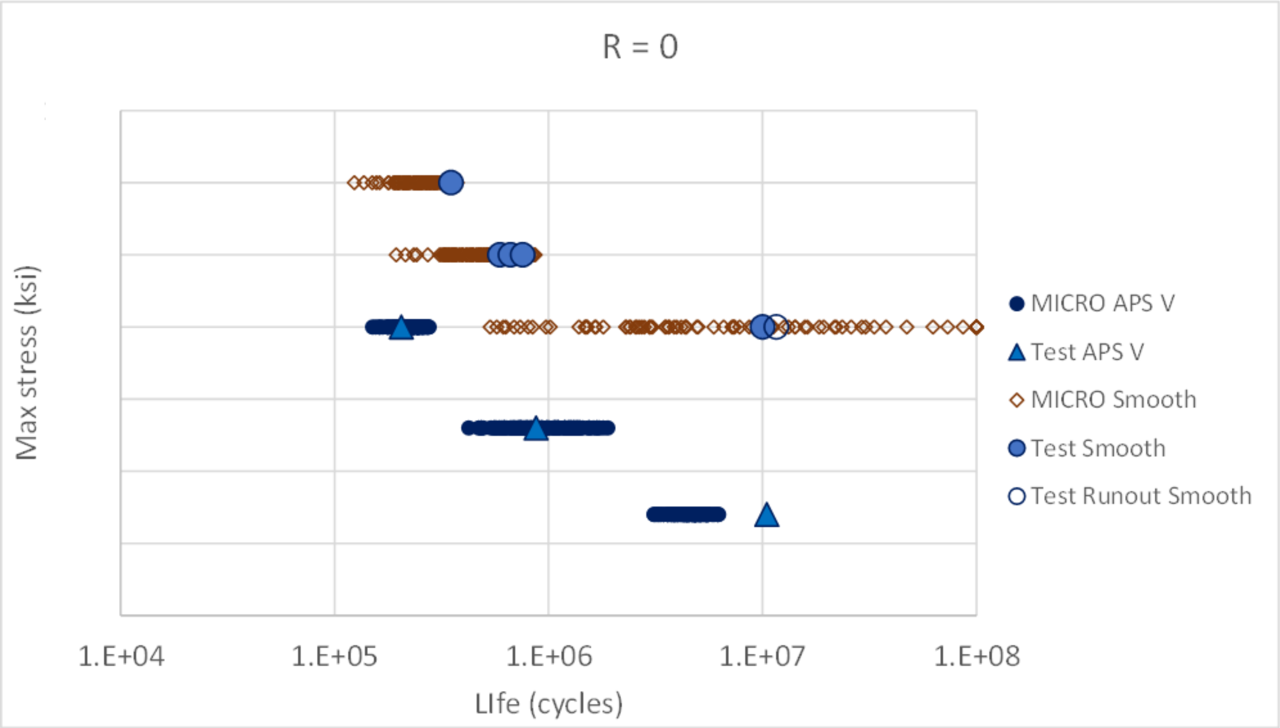
APS Microstructure Surface Layer

- Surface is different from core
  - –Grains have few carbides
- Depleted region is free of second-phase particles (carbides and laves phase)
- Measured micro hardness, and estimating the change in yield strength and grain boundary strength
  - –Surface to core matrix hardness .87 to 1
  - –Surface to core matrix yield strength 0.8 to 1
  - –Assume surface to core frictional strength 0.8 to 1
  - –Assume reduction in grain boundary strength



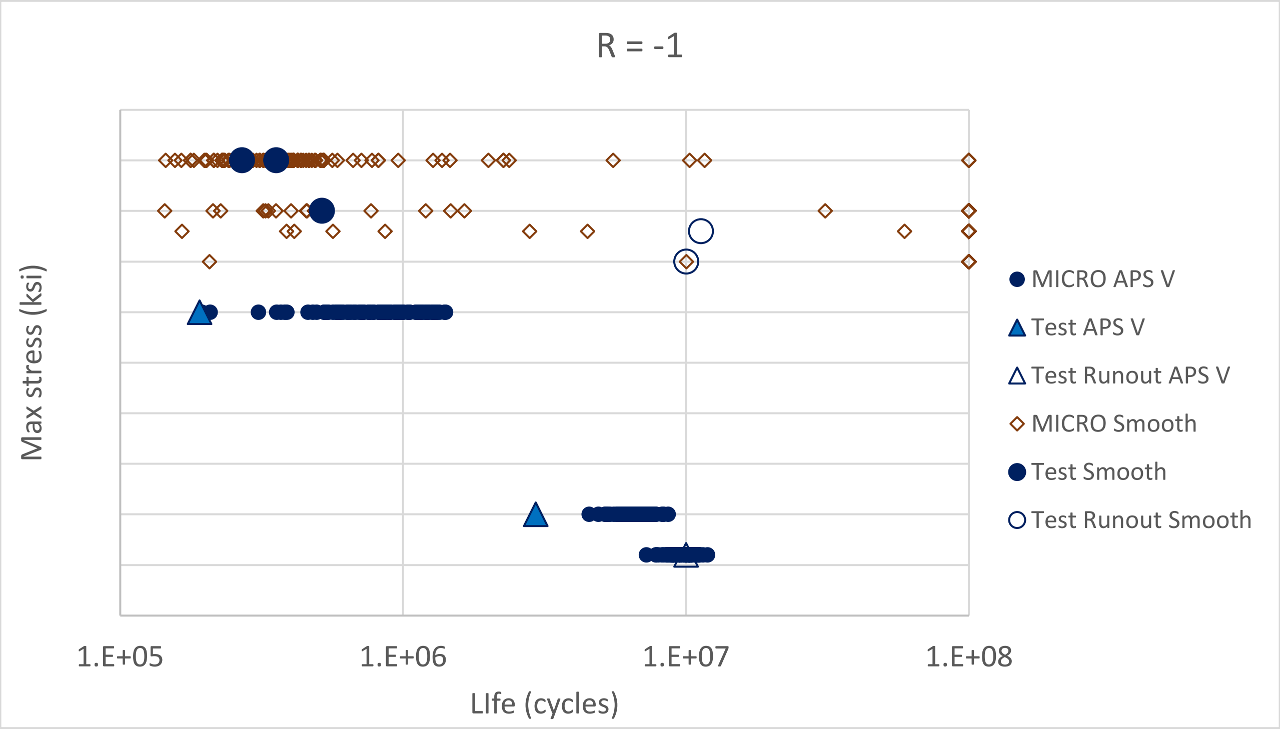
VPS-MICRO Predictions for As-Printed Surface

- Model calibrated to smooth R = 0 material parameters used for APS
- Surface roughness stress K_t and surface layer properties changed
- 100 specimens generated at each stress level
- Model predicts fatigue lives for APS



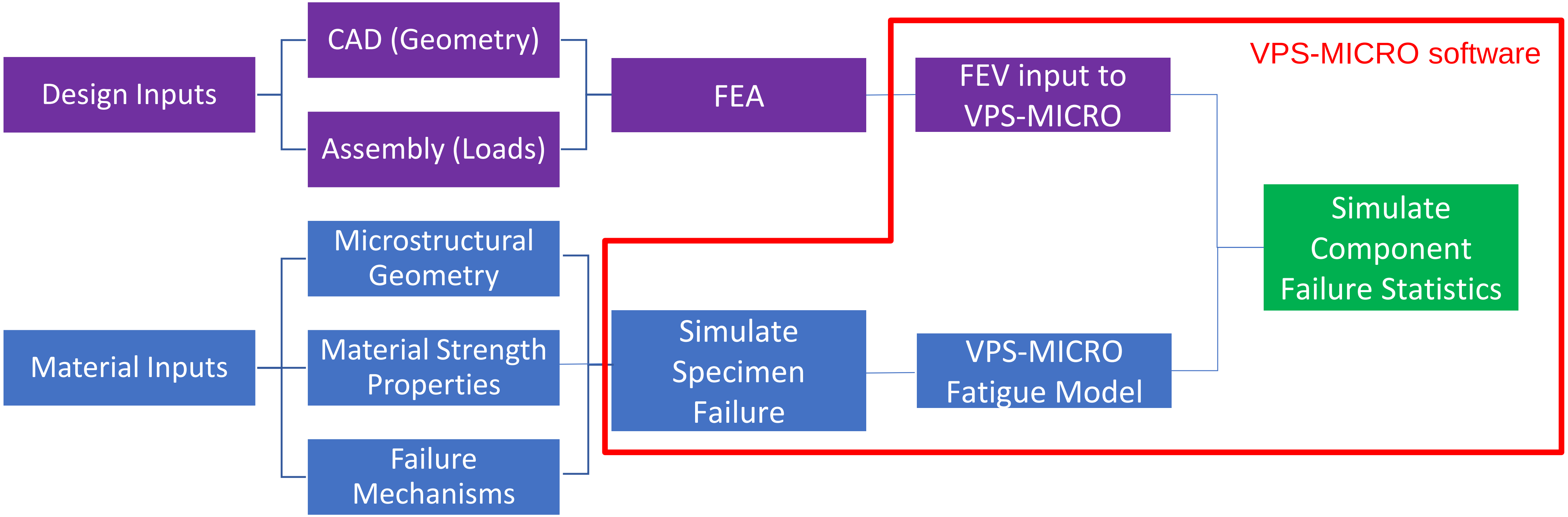
VPS-MICRO Predictions for APS with Different Load Ratio

- Model based on APS R = 0
  - Model calibrated to smooth R = 0 material parameters
  - Surface roughness stress K_t and surface layer properties changed
- Only max and min stress levels changed to model R = -1
- 100 specimens generated at each stress level
- Model predicts fatigue lives for APS *and* different load ratio



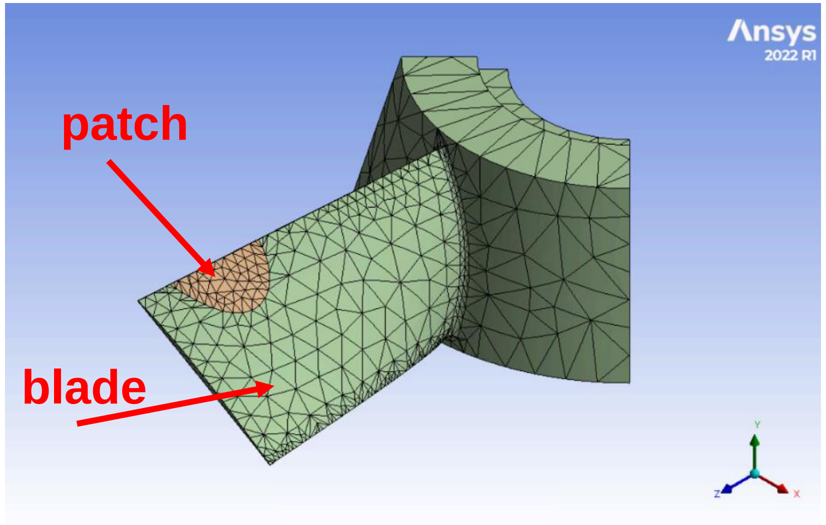
SWP Applied to AM Blade Repair

- Standard work protocol is unchanged from specimen analysis

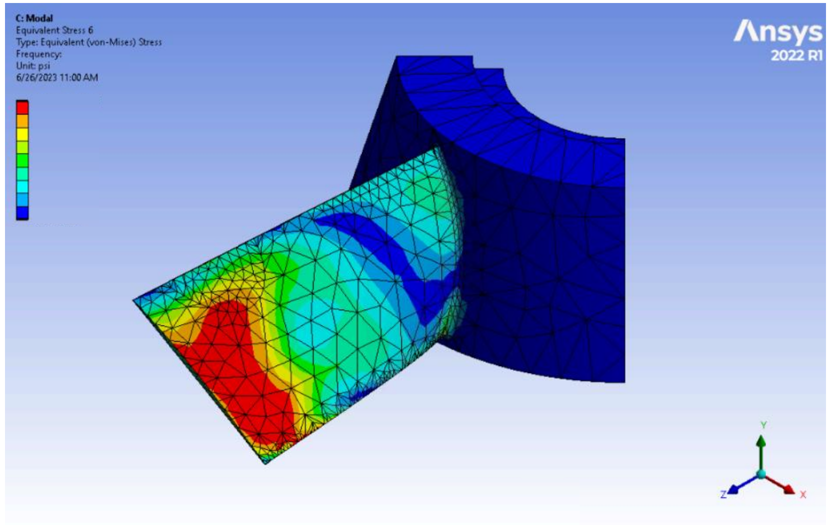


Engine Airfoil Design Inputs

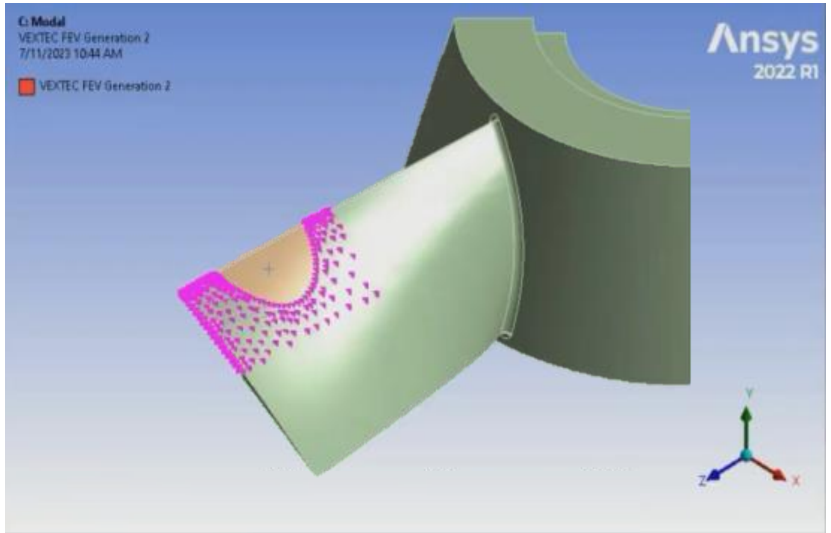
- Original blade is mill annealed Ti-6Al-4V
- Leading edge repair patch is laser powder DED Ti-6Al-4V
- Ansys modal analysis of mode 6 has high stress in patch
- Ansys extension creates an FEV file with node IDs, areas, and stresses for groups of surface nodes of interest; <u>multi-group FEV files are allowed in VPS-MICRO</u>



AFRL Ansys airfoil meshed model



AFRL Ansys stress results – Mode 6

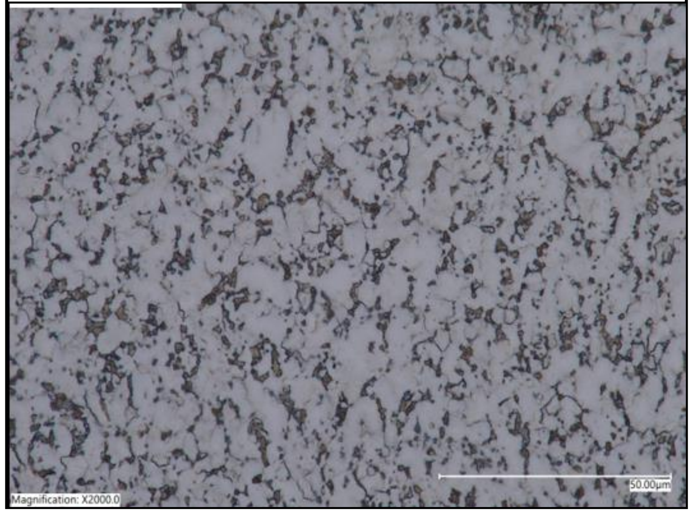


“VEXTEC FEV Generation” extension in Ansys to select **nodes in both the blade & patch regions for the FEV file**

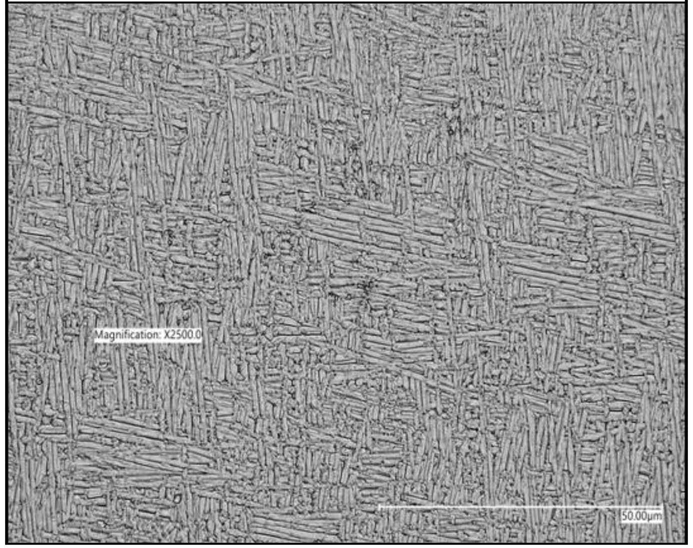
Engine Airfoil Material Inputs from Literature

Material Model Parameter	Conventional Ti-6Al-4V	Powder-DED Ti-6Al-4V
Shear Modulus	44,000 MPa	43,200 MPa
Poisson's Ratio	0.342	0.342
Grain Boundary Strength	2 MPa√m	2.5 MPa√m
Short Crack Coefficient	0.001	0.0001
COV on Micro Stress	0.15	0.12
Volume Fraction	α phase = 0.72; β phase = 0.28	single phase
Specific Fracture Energy	α: 0.391 MN/m; β: 0.391 MN/m	0.131 MN/m
Grain Orientation	α: "schmidhex"; β: "schmidbeta"	"schmidhex"
Grain Size	Lognormal Distribution α: mean 3.43E-5 m; COV 0.2 β: mean 1.36E-5 m; COV 0.25	Lognormal Distribution mean 1.78E-4 m; COV 0.27
Frictional Strength	Lognormal Distribution α: mean 845.3 MPa; COV 0.3 β: mean 760.8 MPa; COV 0.3	Lognormal Distribution mean 911.7 MPa; COV 0.3
Long Crack Growth (Paris Eq. $da/dN = C\Delta K^n$)	n = 3.96; C Lognormal Distribution mean 1.15E-12; COV 0.3	n = 3.8; C Lognormal Distribution mean 1.30E-12; COV 0.45

Conventional Ti-6Al-4V

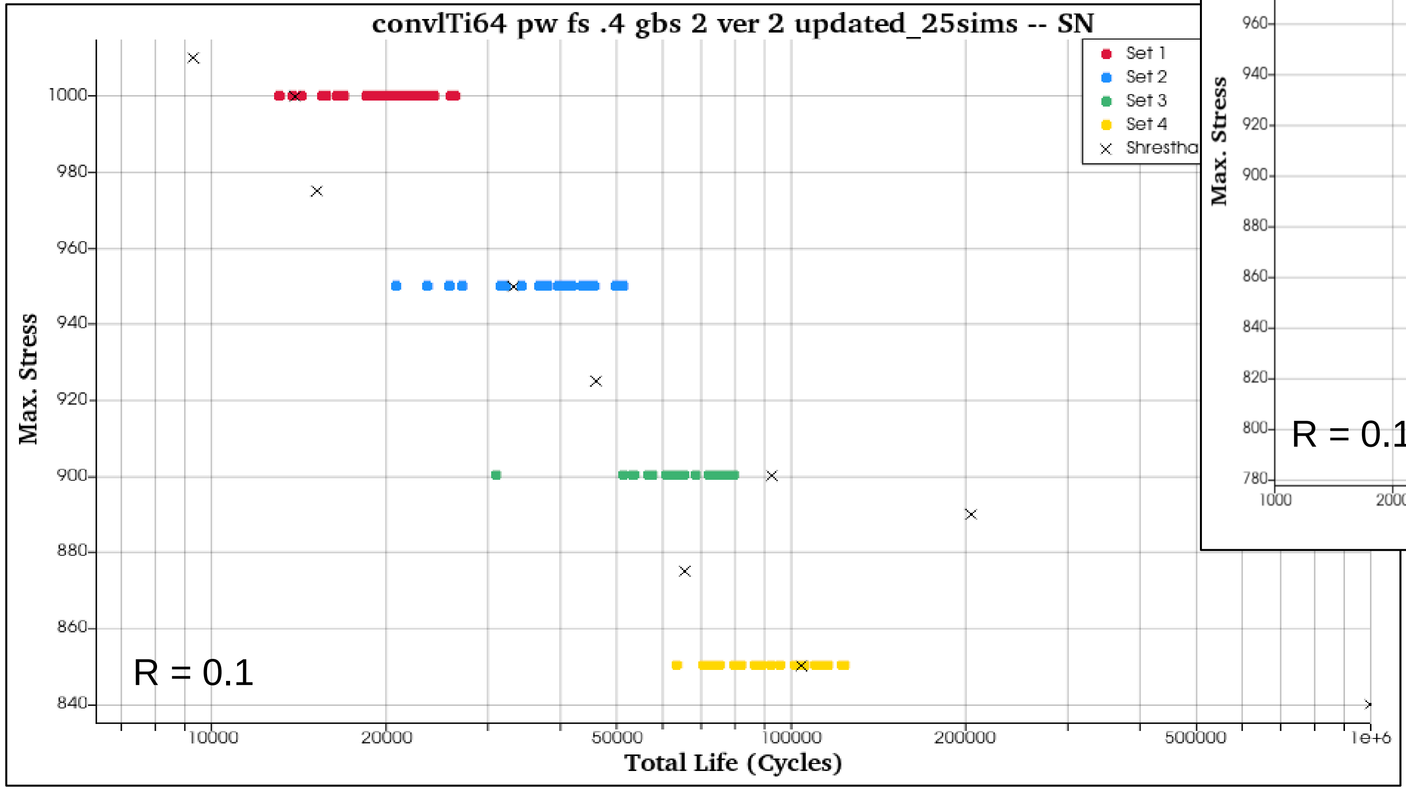


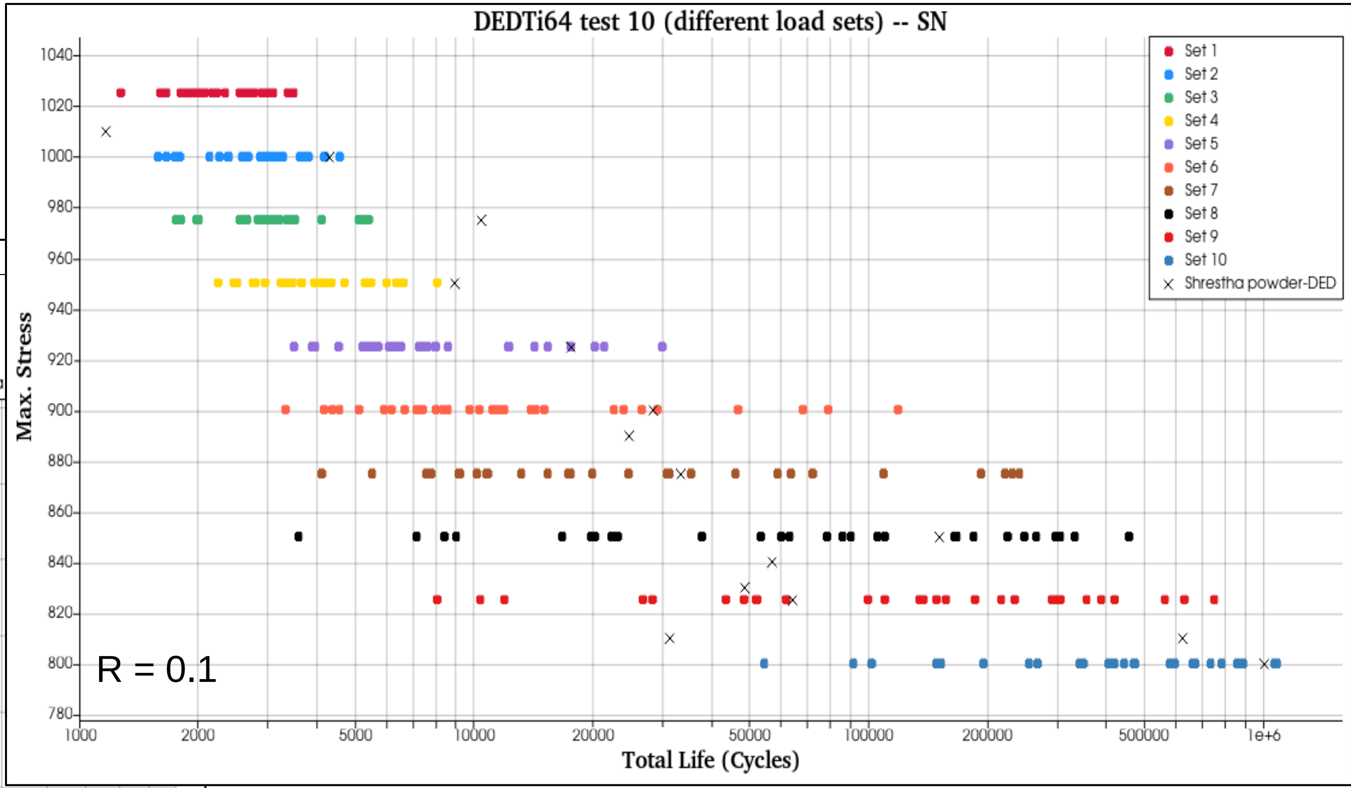
Powder-DED Ti-6Al-4V



Simulation Results – Specimen Geometry

- VPS-MICRO predictions track well with literature-sourced specimen fatigue test data

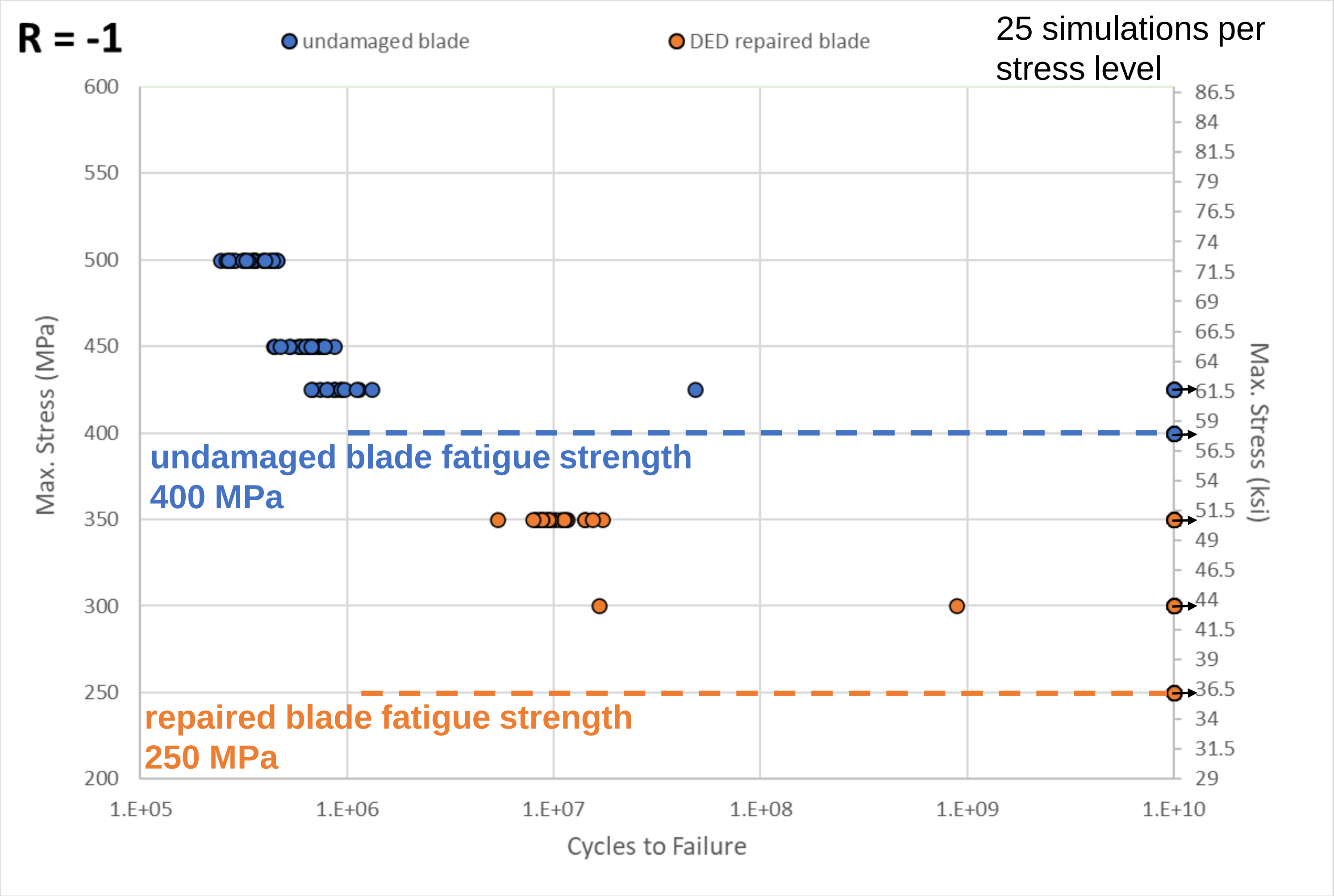




Shrestha, S. (2021). Mechanical Characterization of Ti-6Al-4V Repaired by Directed Energy Deposition in Comparison with the Conventional Ti-6Al-4V (Doctoral dissertation, The University of Akron).

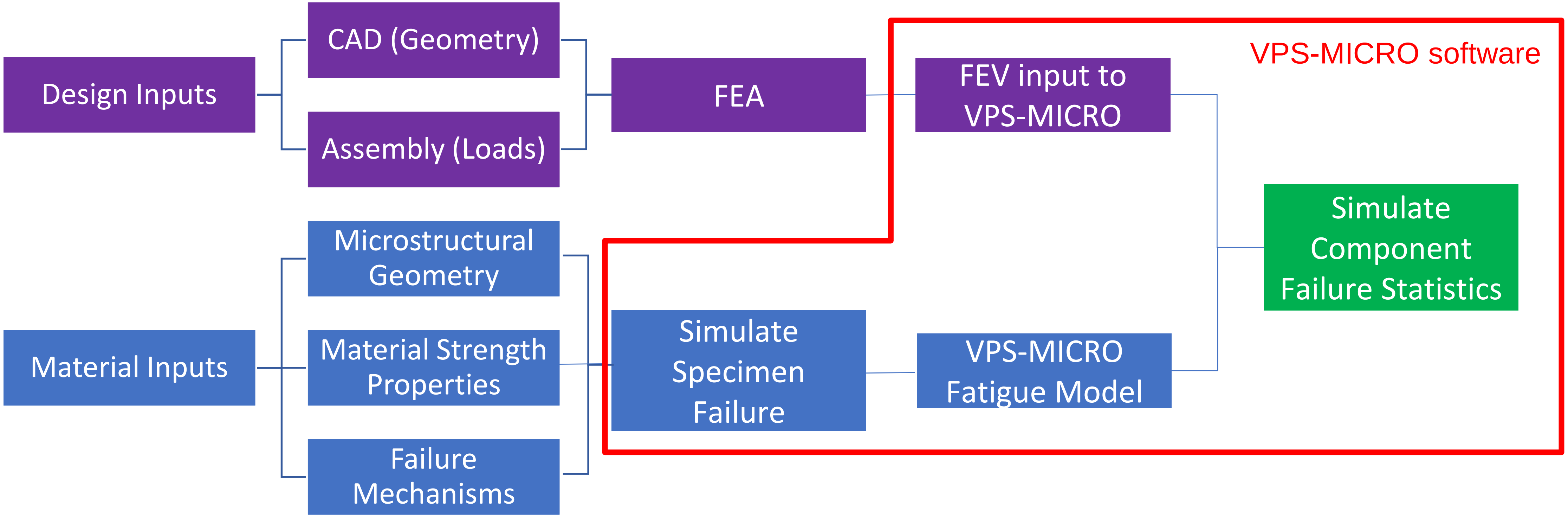
Engine Airfoil VPS-MICRO Analysis

- R = -1 Mode 6 airfoil S-N curves
- Undamaged vs. DED-repaired Ti-6Al-4V
- DED-repaired fatigue strength is lower than undamaged
- **Only VPS-MICRO can provide information on performance at R = -1 loading, since physical tests were only run at R = 0.1**



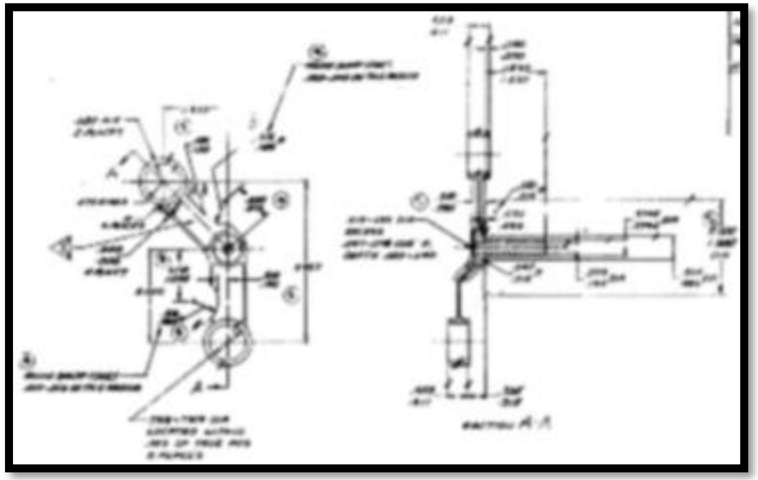
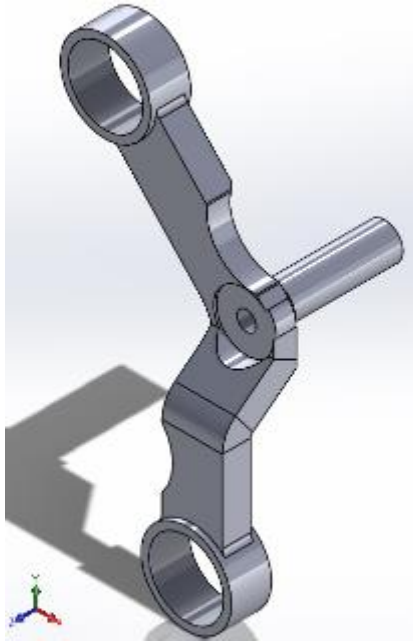
SWP Applied to AM Replacement Bell Crank

- Standard work protocol is unchanged from specimen analysis



Engine Throttle Linkage Bell Crank

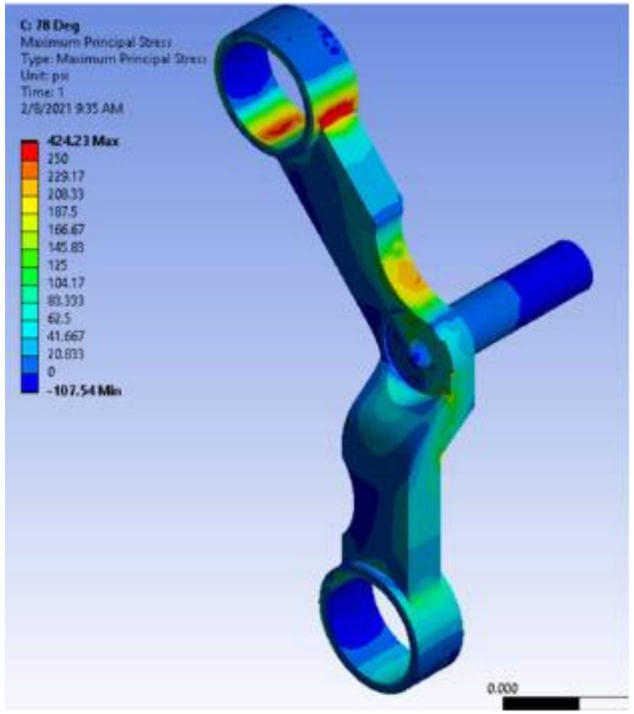
- Current bell crank is cast 410 stainless steel
- Candidate replacement is LPBF CoCr

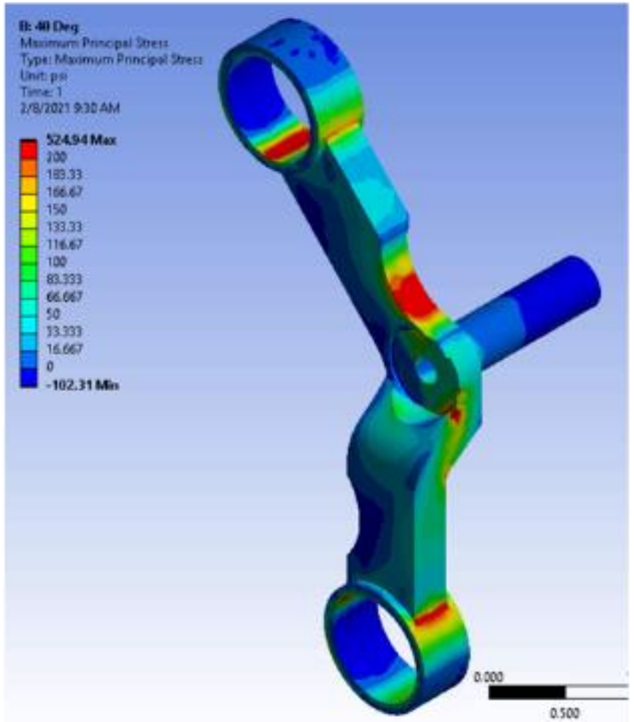
Bell Crank Design Inputs

- FEM of each relative position with 1 lb. load at upper rod. Max stress ~ 0.2 to 0.5 ksi. Different positions had high stresses in different locations. AM material properties can vary with location.

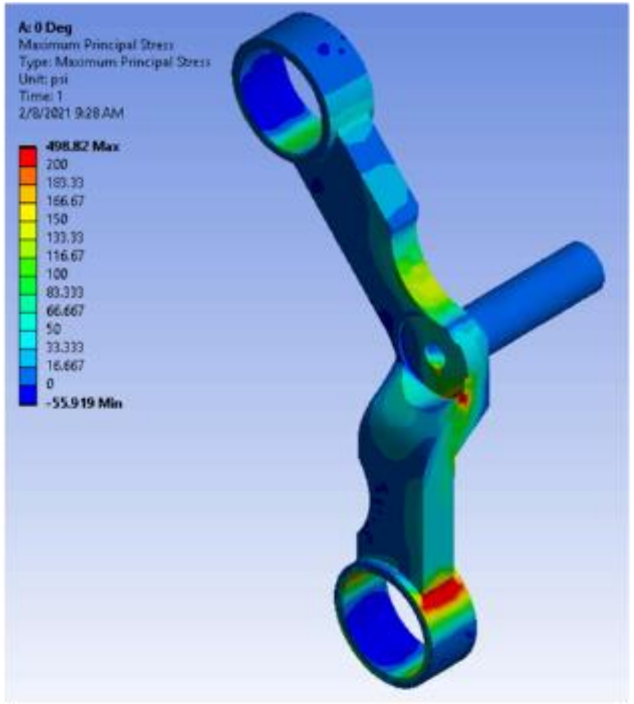
78°



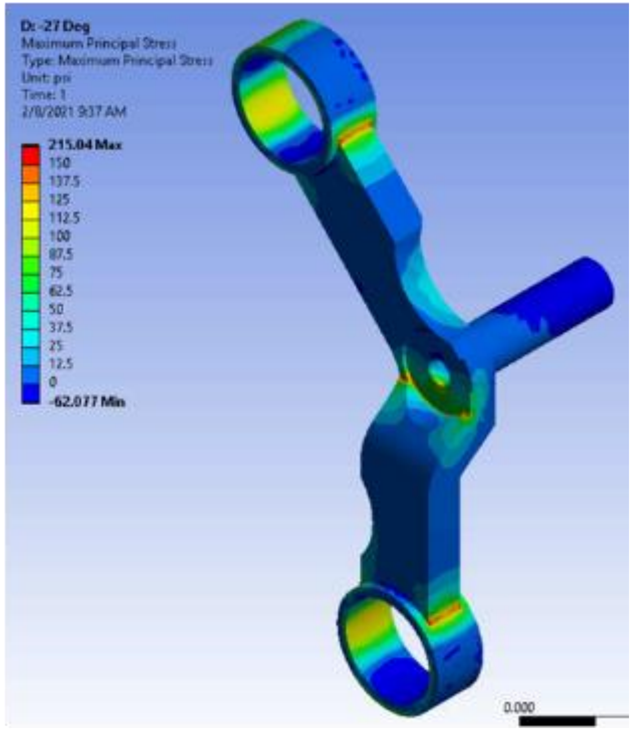
40°



0°

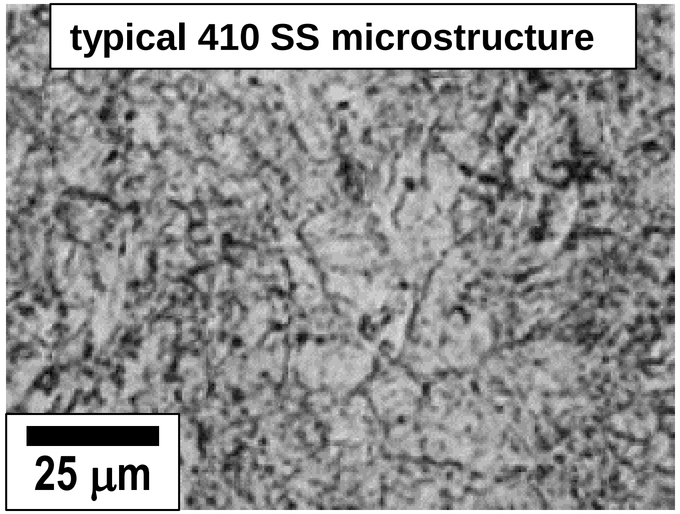


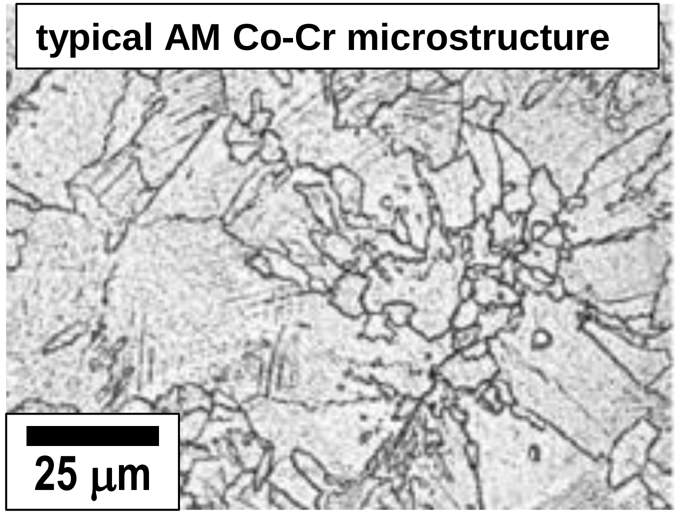
-27°



Bell Crank Material Inputs from Literature

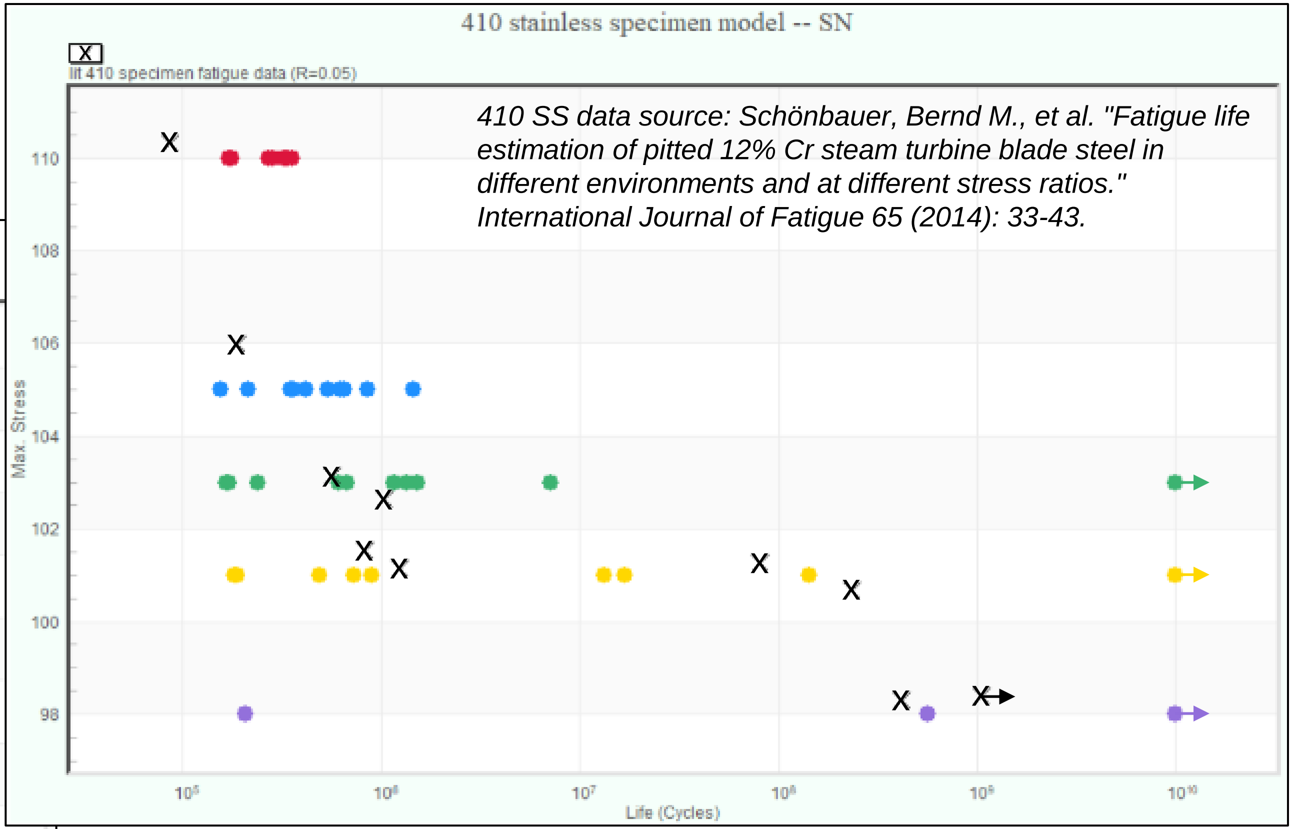
Material Model Parameter	410 Stainless Steel	AM Cobalt Chrome
Shear Modulus	11,328 ksi	11,045 ksi
Poisson's Ratio	0.28	0.275
Grain Boundary Strength	2.02 ksi√in	3.0 ksi√in
Short Crack Coefficient	0.01	0.01
COV on Micro Stress	0.15	0.31
Specific Fracture Energy	2.466 kip/in	1.741 kip/in
Grain Orientation	"Martensite"	"Schmid" (FCC)
Grain Size	Lognormal Dist. mean = 3.543E-4 in, COV = 0.3	Lognormal Dist. mean = 2.681E-3 in, COV = 0.3
Frictional Strength	Lognormal Dist. mean = 102.3 ksi, COV = 0.3	Lognormal Dist. mean = 121.4 ksi, COV = 0.15
Long Crack Growth (Paris Equation $da/dN = C\Delta K^n$)	n = 3.4525; C Lognormal Dist. mean 5.86E-11, COV = 0.45	n = 3.24; C Lognormal Dist. mean 8.015E-11, COV = 0.45

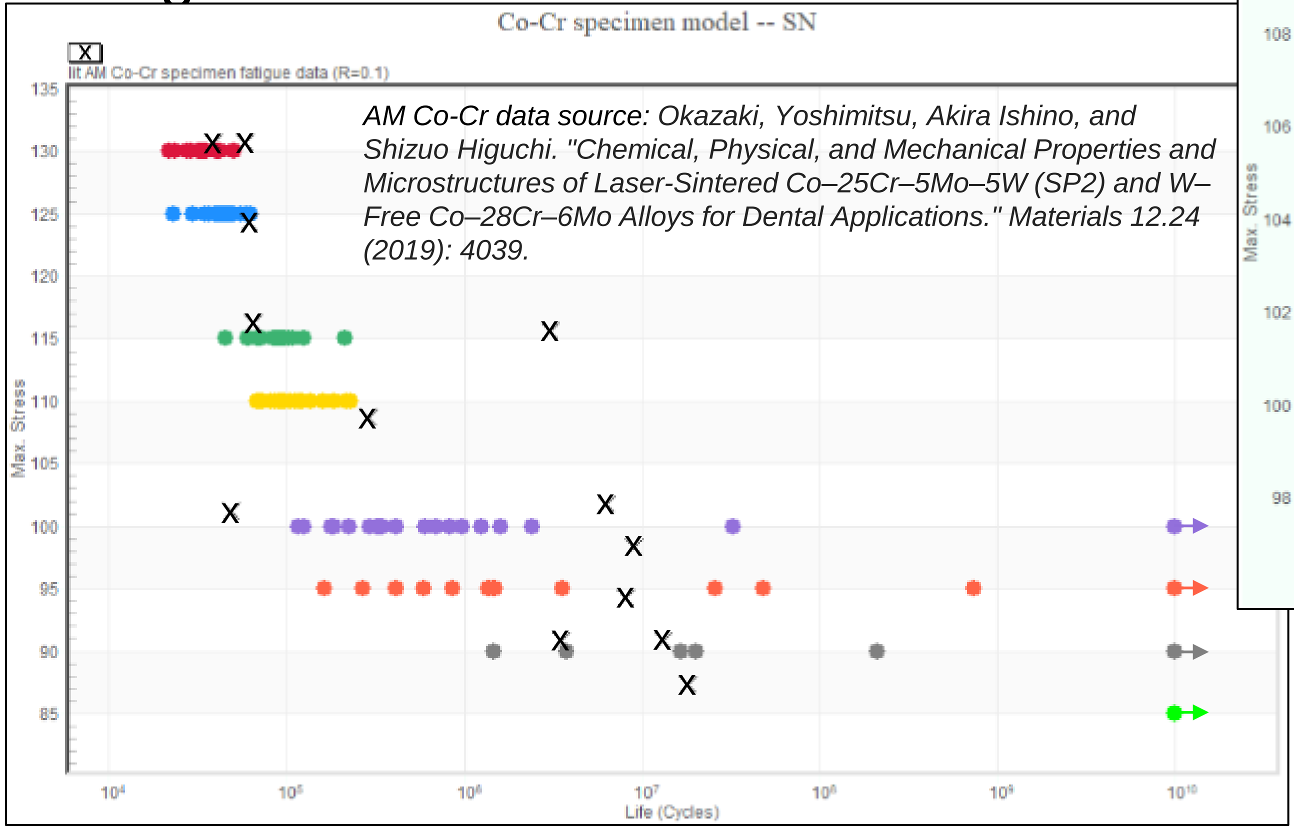




Simulation Results – Specimen Geometry

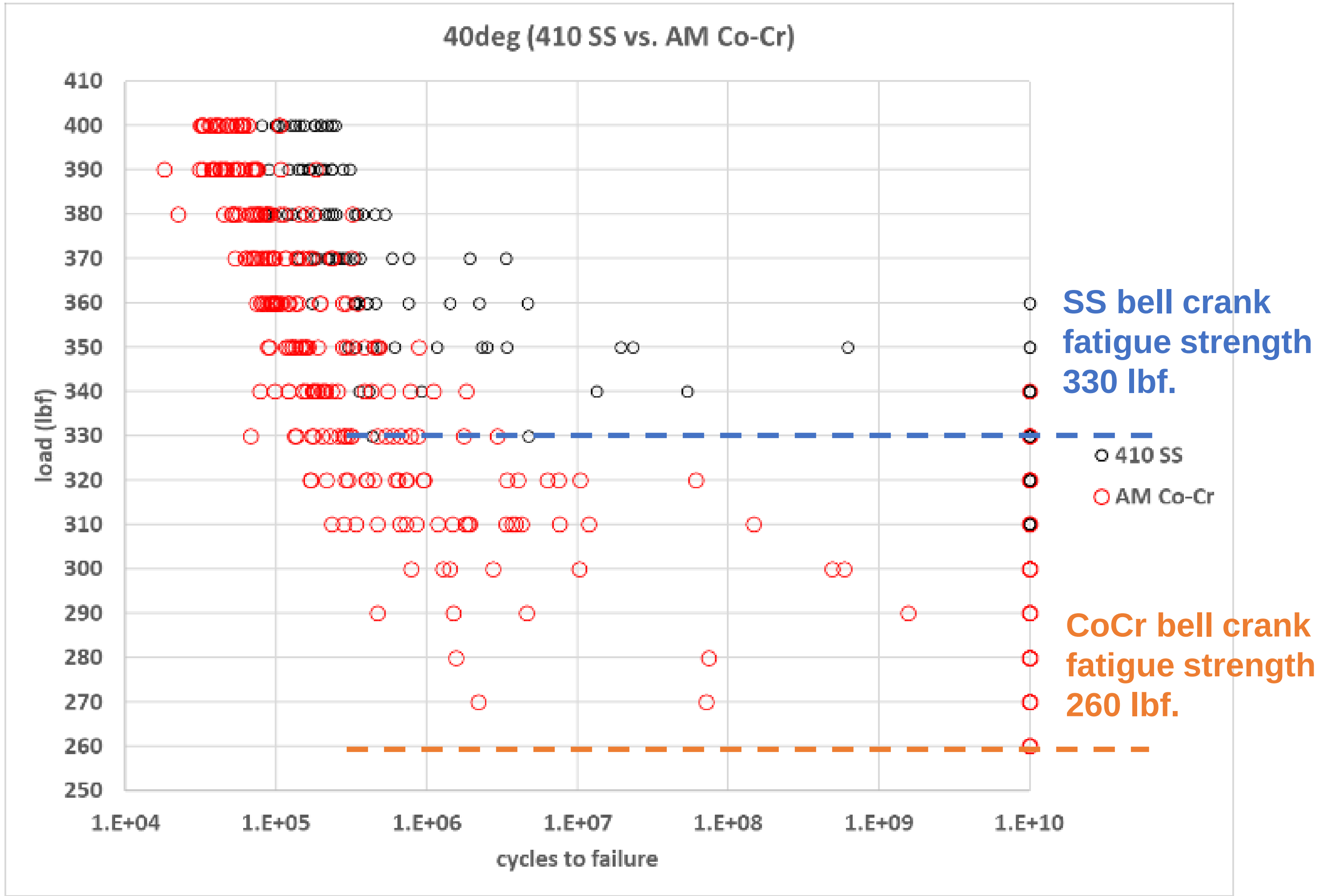
- VPS-MICRO predictions track well with literature-sourced specimen fatigue test data





SWP Analysis Results – Bell Crank

- Bell crank simulated S-N curves at 40 degree operational position
- Conventionally-processed 410 SS vs. AM Co-Cr
- AM Co-Cr fatigue strength is lower than 410 SS
- These quantitative results were achieved before AM parts were built or specimen test data were gathered



AM Development and Certification – potential impact of advanced properties models

Advanced properties models enable

A. Expedited, improved design properties development
B. Improved process control; higher-sensitivity, lower-cost, shorter-schedule
C. Opportunities for accelerated qualification and certification

Typical Duration for a NASA-STD-6030 Class A2 Component

<table>
<tr><th></th><th colspan="2">current typical</th><th colspan="3">future, incorporating advanced properties models</th></tr>
<tr><th>Task</th><th>Task Duration</th><th>Cumulative Duration</th><th colspan="2">Task Duration</th><th>Cumulative Duration</th></tr>
<tr><td>1. Detail material process</td><td>prerequisite</td><td>start</td><td colspan="2">prerequisite</td><td>start</td></tr>
<tr><td>2. Qualify material process</td><td>9 mo.</td><td>9 mo.</td><td colspan="2" rowspan="2">complete in parallel with 4-7</td><td rowspan="2">start</td></tr>
<tr><td>3. Develop design properties</td><td>6 mo.</td><td>15 mo.</td></tr>
<tr><td>4. Detail component design and production plan</td><td>6 mo.</td><td>21 mo.</td><td>6 mo.</td><td rowspan="4">Model and test critical properties</td><td>6 mo.</td></tr>
<tr><td>5. Pre-production article(s) plan, fab, evaluate</td><td>9 mo.</td><td>30 mo.</td><td>6 mo.</td><td>12 mo.</td></tr>
<tr><td>6. Complete AMRR and QPP; finalize production process controls.</td><td>3 mo.</td><td>33 mo.</td><td>3 mo.</td><td>15 mo.</td></tr>
<tr><td>7. Build, acceptance-test and qual. test qual. units</td><td>12 mo.</td><td>45 mo.</td><td>6 mo.</td><td>21 mo.</td></tr>
<tr><td>8. Build and acceptance-test production units</td><td>9 mo.</td><td>54 mo. (4.5 yr.)</td><td colspan="2">6 mo.</td><td>27 mo. (2.2 yr.)</td></tr>
</table>

Conclusions

- VPS-MICRO can be used in preliminary design to assess the suitability of an AM part
- The solution can be used to determine the suitability of machined vs. as-printed surface for an AM part
- Computational modeling can be integrated into certification processes

Thank you!